The Vulnerability of the Dupi Tila Aquifer, Dhaka, Bangladesh

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by

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Abstract

The Dupi Tila aquifer in Bangladesh is of national importance, providing over 95% of the water supply for the capital city, Dhaka. The demand for water is rising inexorably. There is concern about the sustainability of the aquifer and its vulnerability to contamination.

In Dhaka, the Dupi Tila aquifer is confined by the Madhupur Clay. Natural recharge to the aquifer is by vertical leakage through the Madhupur Clay. However, large-scale development of the aquifer since 1971 has continued beyond the rate which could be sustained by vertical leakage. Piezometric levels have steadily declined, aquifer storage has been depleted, the aquifer has become unconfined over large parts of the city, and an extensive cone of depression has developed outwards to the rivers bounding the city.

The extent to which groundwater abstraction can be balanced by induced river recharge and enhanced vertical leakage has been explored by development of a groundwater flow model. Both types of recharge are potential sources of contamination. To assess aquifer vulnerability to contamination, a detailed survey of groundwater quality across Dhaka has been made and related to previous data. A plume of contaminated groundwater is shown to have intruded the aquifer. In addition, a preliminary survey of organic contamination suggests that contaminants from industrial areas are entering the aquifer through the Madhupur Clay. To evaluate the relative impact on groundwater quality of induced river recharge and enhanced vertical leakage, a solute transport model was developed from the groundwater flow model.

Induced recharge from the contaminated River Buriganga is responsible for the plume of low quality groundwater in the South West of the city. Vertical leakage of contaminated urban recharge may affect groundwater quality more widely in the longer term.

Recommendations are made for the protection of the Dupi Tila aquifer as a source of high quality groundwater.

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LIST OF ABBREVIATIONS AND ACRONYMS

BBS	Bangladesh Bureau of Statistics
BGS	British Geological Survey
BHS	British Hydrological Society
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
DoE	Department of Environment
DCC	Dhaka City Corporation
DTW	Deep Tube Well
DWASA	Dhaka Water and Sewerage Authority
EC	Electrical Conductivity
EPC	Engineering and Planning Consultants
GC	Gas Chromatography
GoB	Government of Bangladesh
GSB	Geological Survey of Bangladesh
GWC	Groundwater Circle
HTW	Hand Tube well
IAH	International Association of Hydrogeologists
IAHS	International Association of Hydrological sciences
MMP	Sir Mott MacDonald & Partners Limited
MMI	Mott MacDonald International
MPO	Master Plan Organisation
MS	Mass Spectrometry
PWD	Public Works Datum
SoB	Survey of Bangladesh
UCL	University College London
US EPA	United States Environment Protection Agency
USGS	United States Geological Survey
WARPO	Water Resources Planning Organisation

CHAPTER 1 INTRODUCTION

1.1 The Concept of Aquifer Vulnerability

The term 'vulnerability' began to be used in hydrogeology in the late 1960s in France (Margat, 1968; Albinet and Margat, 1970) and more widely in 1980s (Haertle, 1983; Aller *et al.*, 1987). The concept of aquifer vulnerability is based on the fact that the natural environment can provide some degree of protection to groundwater against adverse impacts, particularly with reference to contaminants. Contemporary vulnerability assessment, however, goes far beyond this basic concept. Vrba and Zaporozec (1994) defined groundwater vulnerability as 'an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts'. In addition to intrinsic (i.e. hydrogeological) characteristics of a groundwater system and the overlying soil, account may be taken of specific characteristics of contaminants e.g. the possibility of sorption or chemical degradation and their management practice. Consequently, the concept of vulnerability has been extended, so that specific (integrated) as well as intrinsic (or natural) vulnerability can be recognized. Furthermore, the concept of aquifer vulnerability is not related to water quality aspects only; it can also refer to aspects of groundwater resource sustainability (Adams and MacDonald, 1998). Aquifers may be vulnerable to both contamination and unmanaged exploitation or both. Some aquifers are more vulnerable than others and recently there has been a great emphasis on mapping aquifer vulnerability in many parts of the world (Enquinst, 1989; Palmer *et al.*, 1995; Zaporozec, 1993; Vrba and Zaporozec (1994).

The concept of aquifer vulnerability recognizes that the risks of pollution from a given activity are greater in certain hydrological, geological and soil situations than others. The concept has been developed as a qualitative tool to make comparative judgement between different aquifers and/or different areas to assist environmental management, with the aim of preventing or minimizing contamination. A number of vulnerability assessment techniques have been developed (Walker, 1969; Albinet, 1970; Vierhuff, 1981; Vilumsen *et al.*, 1983; Goldberg and Gazda, 1984; Aller *et al.*, 1987; Sotornikova and Vrba, 1987; Gossens and van Damme, 1987; Carter *et al.*, 1987; Foster, 1987; Goldberg, 1993; Vrba and Zaporozec, 1994; Zektser *et al.*, 1995; Kukuri *et al.*, 1998; and Maxe and Johansson, 1998). Groundwater vulnerability assessment has been conducted in many countries as a part of comprehensive groundwater protection strategies (Barber *et al.*, 1993; Vrba and Zaporozec, 1994; Civita, 1994; and Lindstrom and Scharp, 1995) during the past decade. The geological and hydrogeological parameters considered relevant in vulnerability assessment vary widely from country to country (context to context). The main attributes used in the assessment of intrinsic groundwater vulnerability are recharge pattern, soil properties, characteristics of the unsaturated zone and transport properties of the aquifer. Attributes of secondary importance include topography, groundwater/surface water interrelation, and the nature of the underlying unit of the aquifer.

Two widely used vulnerability evaluation methods are DRASTIC (Aller *et al.*, 1987) and GOD (Foster and Hirata, 1991). DRASTIC, developed in the USA, is the most widely applied. This method uses seven hydrogeological parameters: depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadoze zone (I) and hydraulic conductivity (C) of aquifer. Each parameter is given a rating range and numerical weighting factor. The limitations of the DRASTIC method as a measure of aquifer vulnerability have been evaluated through a number of studies in which DRASTIC vulnerabilities have been compared to the actual incidence of pollution (Holden *et al.*, 1992; Bates *et al.*, 1993; Kalinski *et al.*, 1994; Eaton and Zaporozec, 1997 and Foster, 1998). Vrba and Zaporozec (1994) consider that the greatest weakness of the

DRASTIC method is its lack of flexibility for adaptation to specific needs. More specifically it underestimates the vulnerability of fractured, compared to unconsolidated aquifers (Rosen, 1994). Several users of DRASTIC identified a number of shortcomings with this system and tried to deal with these difficulties by adjustments and modifications (Cavallin *et al.*, 1987; Evans and Myers, 1990; Lance *et al.*, 1990; Liddle *et al.*, 1989; Moore, 1989; Rosen, 1994; Trojan and Perry, 1988; US EPA, 1991; Zaporozec, 1987). The GOD method is similar in concept, estimating vulnerability of an aquifer through multiplying three discrete phases representing three sets of information: a) type of groundwater occurrence (G); b) lithology overlying the aquifer (O); and c) depth to the phreatic level or top of the aquifer (D). This method has a simple and pragmatic structure, which makes it superior to DRASTIC for interpreting results. However, neither the DRASTIC nor the GOD methodology is spatially based. One of the challenges of assessing groundwater vulnerability in urbanizing areas is the difference in the geological and hydrogeological data available in urban compared to rural settings. Analysis of these data needs to be reasonably uniform in order to classify areas of differing contamination potential. As a result, methods combining GIS and modelling have recently been recommended by various authors (Eaton and Zaporozec, 1997; Kukuri *et al.*, 1998).

The Groundwater Protection Policy (GPP) of the Environment Agency for England and Wales incorporates a concept of aquifer vulnerability (NRA, 1992). The vulnerability system, designed for use in the GPP maps, zones the soil and geological horizons of the unsaturated zone in terms of their physical and chemical properties in order to assess the ease with which a pollutant released at the surface would be likely to reach the underlying groundwater body (Palmer *et al.*, 1995). The aquifer pollution vulnerability systems currently adopted in England (Foster and Adams, 1992; NRA, 1992; Robins *et* *al*., 1995 and Palmer and Lewis, 1998) classify, by lithology and thickness, the predominant strata above the saturated aquifer as the principal indicator of pollution vulnerability, and integrate this with the factors describing the attenuation capacity of the soil zone. A novel element of the new British approach is the way the soil zone is incorporated into the overall scheme. Vulnerability assessment is often identified with the application of vulnerability mapping, which has been developed widely in recent years mostly due to the development of GIS systems. Vulnerability mapping is the spatial description of geological and hydrogeological factors, giving a display in a map form that is understandable and useful to environmental managers. Vulnerability maps demonstrate which areas and/or aquifers are more vulnerable to contamination and where it is necessary to protect groundwater from activities that are potentially polluting. The ultimate objective is to protect the aquifer from contamination. However, recent classifications (NRC, 1993; Vbra and Zaporozec, 1994) include some more interpretive elements, such as results of groundwater modelling, in addition to the essentially qualitative or semi-qualitative approaches in vulnerability assessment previously described.

Specific vulnerability is usually assessed in terms of the danger of the groundwater system becoming exposed to loading by a specific contaminant. Residence time and the attenuation capacity of the soil-rock-groundwater system with respect to individual contaminants are the most important parameters in the assessment of specific groundwater vulnerability. Vulnerability depends partly on the extent to which pollutants are attenuated between the land surface and the water table and partly on the rate with which water and its accompanying pollutants travel through the aquifer. The nature of the aquifer material is therefore of great importance in assessing vulnerability. However, the classical vulnerability assessment provides a qualitative approach to understanding the likelihood of entry and attenuation of pollution. The concept of aquifer vulnerability applied to the Dupi Tila aquifer in Dhaka city is discussed further in Section 4.10.

1.2 Groundwater in Cities - Problems of Urban Hydrogeology

At present, more than half the world's population depends on groundwater for survival (UNESCO, 1996). Groundwater plays a fundamental, but often unrecognized, role in the urban environment in many parts of the world. This critical role is very important in shaping the economic and social health of many urban areas. Although no comprehensive statistics exist on the proportion of urban water supply derived from groundwater world-wide, more than 1 billion urban dwellers in Asia and 150 million in Latin America probably depend directly or indirectly upon well, spring and borehole sources (Foster *et al.*, 1998). Many cities in the world are dependent on groundwater for part or even all of their water supply. Indeed many of these cities developed precisely because of the availability of groundwater of good quality to provide potable supplies where surface water sources were either non-existent or of doubtful quality. Where cities obtain their water supply from surface water sources, groundwater may still make a very significant contribution of the public supply. Table 1.1 indicates the importance of groundwater in many cities and the range of problems that threaten the sustainability of its use.

During the 20th century, cities have grown to sizes unprecedented in human history. The two factors that have dominated world demographic trends in the 20th century are an accelerated rate of population growth and continued migration from rural areas to cities. The result has been a continuous rise in the proportion of the world's population living in urban areas, from less than 15% in 1920 to over 40% in 1990. Estimates are that by the year 2000 about 50% of the world's population will be urban dwellers (UNCHS, 1987).

Table 1.1 The importance of groundwater and groundwater-related problems in cities (after Foster, et al., 1998)

City	Country	Information status	Role of groundwater	Groundwater problems	City	Country	Information status	Role of groundwater	Groundwater problems
Latin America					***Asia***				
Buenos Aires	Argentina	3	min*	urb poll	Dhaka	Bangladesh	2	SS*	gwl
Mar de Plata	Argentina	2	maj	sal int	Beijing	China	3	min*	urb poll
Salta	Argentina	3	maj	urb poll	Shenyang	China	2	maj*	gwl, d-s poll
Santa Cruz	Bolivia	1	SS*	urb poll	Jinzhou	China	2	maj	d-s poll
Cochabamba	Bolivia	3	maj*	gwl	Tianjin	China	1	maj	sub
Santiago	Chile	2	min	urb poll	Shijianhuang	China	3	maj	urb poll, d-s poll
Cali	Colombia	3	min*	urb poll	Lucknow	India	3	maj*	urb poll
San Jose	Costa Rica	1	maj	d-s poll	Nagpur	India	3	maj*	urb poll
Guatemala city	Guatemala	2	maj	d-s poll	Jakarta	Indonesia	3	min*	sal int
San Pedro Sula	Honduras	2	maj*	urb poll	Bandung	Indonesia	2	maj*	urb poll
Mexico DF	Mexico	2	maj	sub	Semarang	Indonesia	2	min*	gwl, urb poll
Leon-Guanajuato	Mexico	1	maj*	d-s poll	Surakarta	Indonesia	3	maj*	urb poll
Chihuahua	Mexico	2	SS	gwl, d-s poll	Manila	Philippines	2	min*	sal int
Queretaro	Mexico	2	maj	sub, urb poll	Cebu City	Philippines	3	maj*	urb poll, sal int
Merida	Mexico	1	maj*	urb poll	Jaffna	Sri Lanka	1	SS*	urb poll, sal int
Managua	Nicaragua	2	maj	urb poll	Bangkok	Thailand	2	maj*	urb poll, sal int
Lima	Peru	2	maj	gwl	Hat Yai	Thailand	1	min*	urb poll, sal int
Ica	Peru	3	SS*	urb poll	Hanoi	Vietnam	3	maj	urb poll
El Tigre	Venezuela	2	SS	urb poll	Sana	Yemen	2	maj	urb poll, gwl
Caribbean Basin					***Africa***				
Nassau	Bahamas	2	maj*	urb poll, sal int	Abidjan	Cote Ivoire	3	min*	urb poll
Bridgetown	Barbados	1	SS	urb poll	Cairo	Egypt	3	min	urb poll
Bermuda	Bermuda	1	maj	urb poll	Dakar	Senegal	3	min*	urb poll
Santo Domingo	Dom. Rep.	2	SS*	urb poll, sal int	Lusaka	Zambia	3	maj*	urb poll, gwl

* Major private, domestic/industrial use, d-s poll (Down stream groundwater pollution), gwl (Falling groundwater levels), maj (Major source of public supply), min (Minor source of public supply), SS (Sole source of public supply), sal int (Aquifer saline intrusion), sub (Land subsidence), urb poll (Groundwater pollution within urban area), 1 (Fully survey data), 2 (Useful summary document), 3 (General background only)

Many problems in urban areas are water-related; these include environmental, health-related, economic and geotechnical issues. It has become clear that urban water - related issues have become a predominant challenge for environmental management for the 21st century. Water shortage is a rapidly growing problem and delivery of safe drinking water cannot be ensured. Scarcity and management of groundwater pose a serious and growing threat to sustainable urban development in small and large cities throughout the world.

A unique combination of hydrology, chemistry and infrastructure exists that leads to particular effects on groundwater beneath urban areas. Yet although urban hydrology is a well established sub-discipline (Lazaro, 1979 and Hall, 1984), the term 'urban hydrogeology' or 'urban groundwater' has been widely used only since 1993. In that year, the International Association of Hydrogeologists (IAH) Oslo congress founded a special Commission on Groundwater of Urban Areas (CGUA). The CGUA conducted workshops in Adelaide (1994), Edmonton (1995) and Aachen (1996) to promote the concept and approaches to the problem of 'urban hydrogeology'. The 27th congress of the IAH at Nottingham, UK (1997) focused on the theme 'Groundwater in the Urban Environment' and discussed a wide range of aspects and perspectives of groundwater in the urban environment. During the past five years the Hydrogeology Group of the British Geological Survey (BGS) have carried out urban groundwater research projects in many developing cities (Foster *et al.*, 1998; Morris *et al.*, 1994; Lawrence *et al.*, 1997). Now 'urban hydrogeology' or 'urban groundwater' is established as an important sub-discipline in its own right. Groundwater has often been the preferred source for urban water supply due to its relatively low cost, high quality and ready availability. Yet groundwater is "out of sight" beneath the ground and so it is often "out of mind" in the consideration of potentially damaging land-use activities. In most cases, urbanization affects underlying groundwater systems in the following two general ways:

- By radically changing patterns and rates of aquifer recharge
- By adversely affecting the quality of groundwater.

Urbanization has a profound effect on groundwater recharge. Urban development may seriously deplete direct recharge to groundwater by sealing large areas of the ground surface with impermeable materials and increasing runoff. Yet, the urban recharge pathways are more numerous and more complex than in rural environments, and many of them may actually enhance recharge, hence compensating for any loss of direct recharge due to "impermeablilisation" (Lerner, 1990; Lerner, 1997). The hydrological pathways are altered in urban areas (Figure 1.1) and the water supply can also find a variety of routes to recharge groundwater as shown in Figure 1.1. The depletion in direct recharge may also be offset by an increase in new types of indirect recharge. The main sources responsible for this increase include leaking water mains and sewers (the water supply may be imported from outside the city), in situ wastewater disposal and urban drainage soakaways. The contribution of these sources to aquifer recharge can be extremely difficult to quantify and the net effects of the water supply system can not be generalized across all cities. According to Foster *et al.* (1994), urbanization generally results in significant increases in groundwater recharge when cities are built on unconfined or semi-confined aquifers. However, the complexity of urban infrastructure will always make it difficult to measure or estimate recharge rates properly. Therefore, the main question is likely to remain unanswered: 'Too much or too little recharge in urban environments'? (Lerner, 1997).

Urbanization has serious effects on groundwater quality and many of these are poorly known and depend on local circumstances. Urbanization and overabstraction of groundwater beneath some large cities of the world has resulted serious groundwater quality deterioration (Boonyakarnkul *et al.*, 1992; Eisen and Anderson, 1980; Ford and

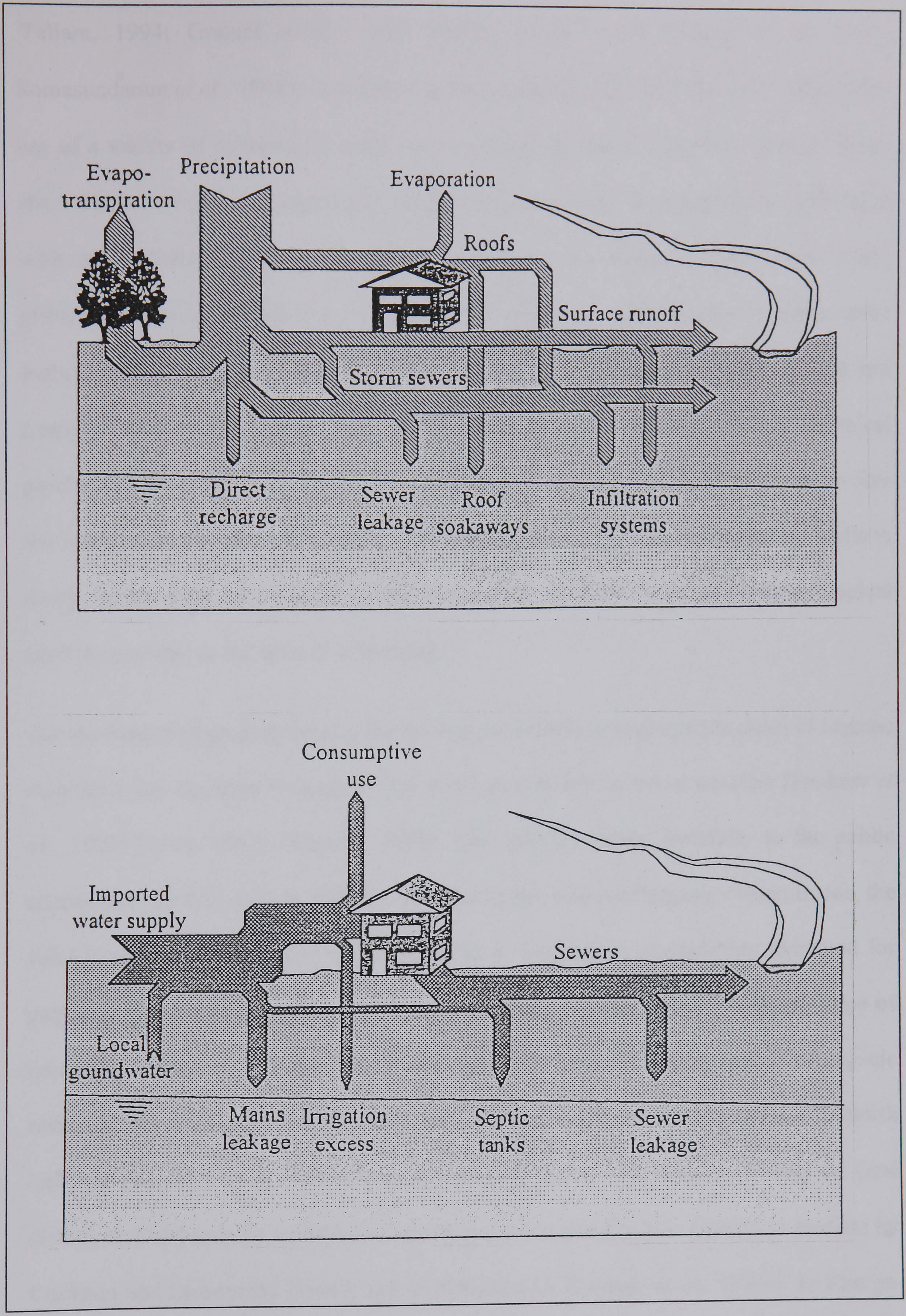


Figure 1.1 *Urban pathways for recharge, from precipitation (top), from water supply and waste (bottom) (after Lerner, 1997)*

Tellam, 1994; Graniel *et al.*, 1999; Morris, *et al.*, 1994; Nazari *et al.*, 1993; Somasundaram *et al.*, 1993;). A primary concern of urban development is the widespread use of a variety of contaminants that can seriously degrade groundwater quality. There are a number of potential sources of groundwater pollution characteristically associated with urban environments (Figure 1.2). As documented by Mather (1994), Lerner *et al.*, (1994) and Lerner & Tellam (1992), potential threats to water quality in urban areas include domestic sewage, industrial sites, landfill sites, spillages during road and rail transport of chemicals, sewers and septic tanks, storage tanks and oil and chemical pipelines. Most cases of inorganic contamination of groundwater in urban areas involve the ions chloride, nitrate and sulphate. Microbiological contamination of shallow wells in many urban areas is believed to be widespread in most types of hydrogeological environment due to the density of housing.

Contamination of groundwater by the inadvertent release or improper disposal of organic chemicals has occurred throughout the world particularly in urban aquifers (Pankow *et al.*, 1996; Fetter, 1993; Chapelle, 1992). This problem came forcefully to the public attention in the mid - to late 1970s when a particular subset of organic contaminants, the volatile organic chemicals (VOCs), was widely detected in groundwater extracted for public drinking water supplies in the United States. This is an environmental issue of increasing concern to many developed nations. Numerous discoveries of organic contaminants at concentrations believed to be harmful to health have been made in North America (Westrick *et al.*, 1984), with typical case studies described in Arizona by Graf (1986), in California by California Department of Health Services (1990), in Indiana by Cookson and Leszcynski (1990), and in Nebraska by Kalinski *et al.*, (1994). In Europe, widespread contamination by VOCs have been reported in heavily industrialized cities such as Milan, Italy (Cavallaro *et al.*, 1986; Zoetman *et al.*, 1981) and in the Midlands of

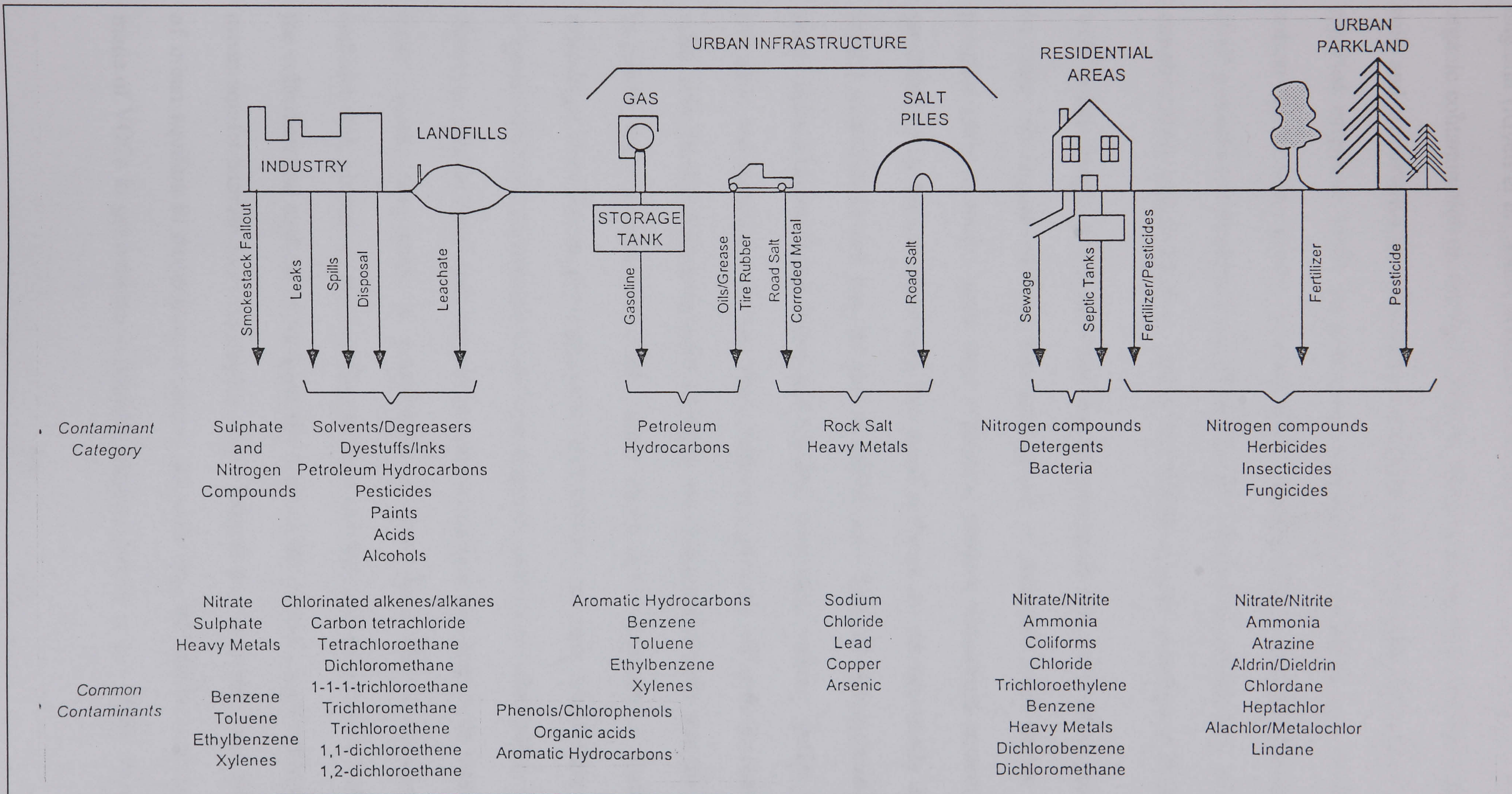


Figure 1.2 Subsurface pathways for urban pollutants (after Howard, 1997)

England (Rivett *et al.*, 1989, Nazari *et al.*, 1993; Burston *et al.*, 1993). An overview of organic contamination in Australia (Knight, 1993) estimates that 7000 sites exist where soils and groundwater are affected by manufactured chemicals. Benker *et al.* (1996) also reported extensive VOCs contamination underlying a residential area in Perth with industry as the likely source. A survey of 15 Japanese cities in 1996 has shown that 30% of all groundwater supplies are contaminated by chlorinated solvents and, in 3% of the samples taken, concentrations exceeded WHO drinking water guidelines (UNEP, 1996).

VOC contamination has in fact been found in almost all surveys of urban groundwater. In many developing countries, the rapid growth of industries often highly dispersed geographically as small - scale units is likely to produce widespread contamination of groundwater by organic chemicals. The worst polluters are not necessarily always the largest industries (which may be able to afford some form of effluent treatment) but small industries producing paper and textiles, processing leather, metals and other materials and repairing vehicles. These industries generate effluents containing spent acids, oils, fuels and solvents, many of which are discharged directly into the ground or to nearby water courses, particularly canals. Small service industries – such as metal workshops, dry cleaners, photo processors and printers – also use considerable quantities of potentially toxic contaminants, and their disposal practices are often poorly controlled. However, despite their increasing use in many developing countries, little monitoring for these organic compounds in groundwater is undertaken. The researchers of BGS consider that, because of the volatility of these solvents and the inherent difficulties in the collection and analysis of samples, the scale of the problem is still unknown in the urban aquifer beneath most developing cities. Despite the commonly high vulnerability of urban aquifers in developing countries, the only city for which a survey has been made of VOCs in groundwater is Merida, Mexico (Goody *et al.*, 1993). This survey of water supply boreholes revealed widespread contamination by chlorinated solvents. Although concentration is generally less than 10 parts per billion, it is considered an underestimation of actual concentrations because of the inherent difficulties of collecting and analyzing samples.

Recent work at the BGS has highlighted this lack of information concerning cities in the developing countries. Dhaka, the fastest growing city in the developing world and with 95% of its water supply obtained from groundwater, provides an important challenge in urban hydrogeology.

1.3 The Study Area- Dhaka City

1.3.1 The Development of Dhaka City

Dhaka, the capital of Bangladesh, is a typical example of a city in which urban development and groundwater resource sustainability are in conflict. Due to rapid urbanization, demand for water is increasing, abstraction is rising and the sustainability of the aquifer is seriously threatened. Groundwater resources are being depleted day by day. To add to the complexity, as new recharge patterns are established, the aquifer becomes vulnerable to contamination from polluted surface water and a number of contaminating activities within the city.

Dhaka is one of the fastest growing cities in the world. The city has a population of 9 million, increasing at more than 6% (BBS, 1995) per year. It is expected to be home of 18 million people by the year 2015. Dhaka city will become a megacity before the end of the decade. The city is expanding so rapidly that it is impossible to keep track for proper planning.

Dhaka city has a history of 400 years and over this time it has expanded from a surface area of 1.5 km^2 to the present size 250 km^2. The city is surrounded by the rivers

Buriganga to the south, Tongi to the north, Turag to the west, and Balu to the east (Figure 1.3). It is located along the north bank of the River Buriganga and the present trend of growth is from south to north. An account of the historical development of Dhaka city is given in the Section 2.3.

1.3.2 Dhaka's Water Supply

Managed water supply in Dhaka dates back more than 100 years (Chowdhury and Faruqui, 1991). Systematic groundwater development started in Dhaka city in 1949 and available records show that groundwater abstraction has increased by more than 700% between 1960 and 1995 (Ahmed *et al.*, 1999). Plio-Pleistocene fluvio-deltaic sands of the Dupi Tila Formation beneath the city form a highly productive aquifer that has been progressively developed for public water supply since the 1970s, and currently provides 0.8 Mm^3/day (million cubic metre per day), more than 95% of the total supply. At present, the Dhaka Water And Sewerage Authority (DWASA) supplies about 250 Mm^3/year from about 220 Deep Tube Wells (DTWs). Yet the total supply meets only half of the current demand. The groundwater supply for Dhaka ctiy is fully described in the Section 2.3.

1.3.3 Geology and Hydrogeology of the Dhaka Region

Dhaka is situated at the southern limit of the fault-bounded Madhupur Tract, across which the Madhupur Clay overlies the Dupi Tila Formation. The Dupi Tila Formation is composed of fine to coarse-grained, fluvio-deltaic sands of Plio-Pleistocene age. The Dupi Tila sands constitute an aquifer system, which is made up of two aquifers separated by a discontinuous clay layer. The Dupi Tila aquifer varies in thickness from 100 to 200 m, whereas the thickness of the Madhupur Clay is about 10 m. Direct recharge to the aquifer is largely reduced by the presence of the clay. Progressive aquifer development has resulted in continued decline of piezometric head in the aquifer, to the extent that it is now unconfined over much of the city. Groundwater occurs at a depth of 25-30 m in the central part of the

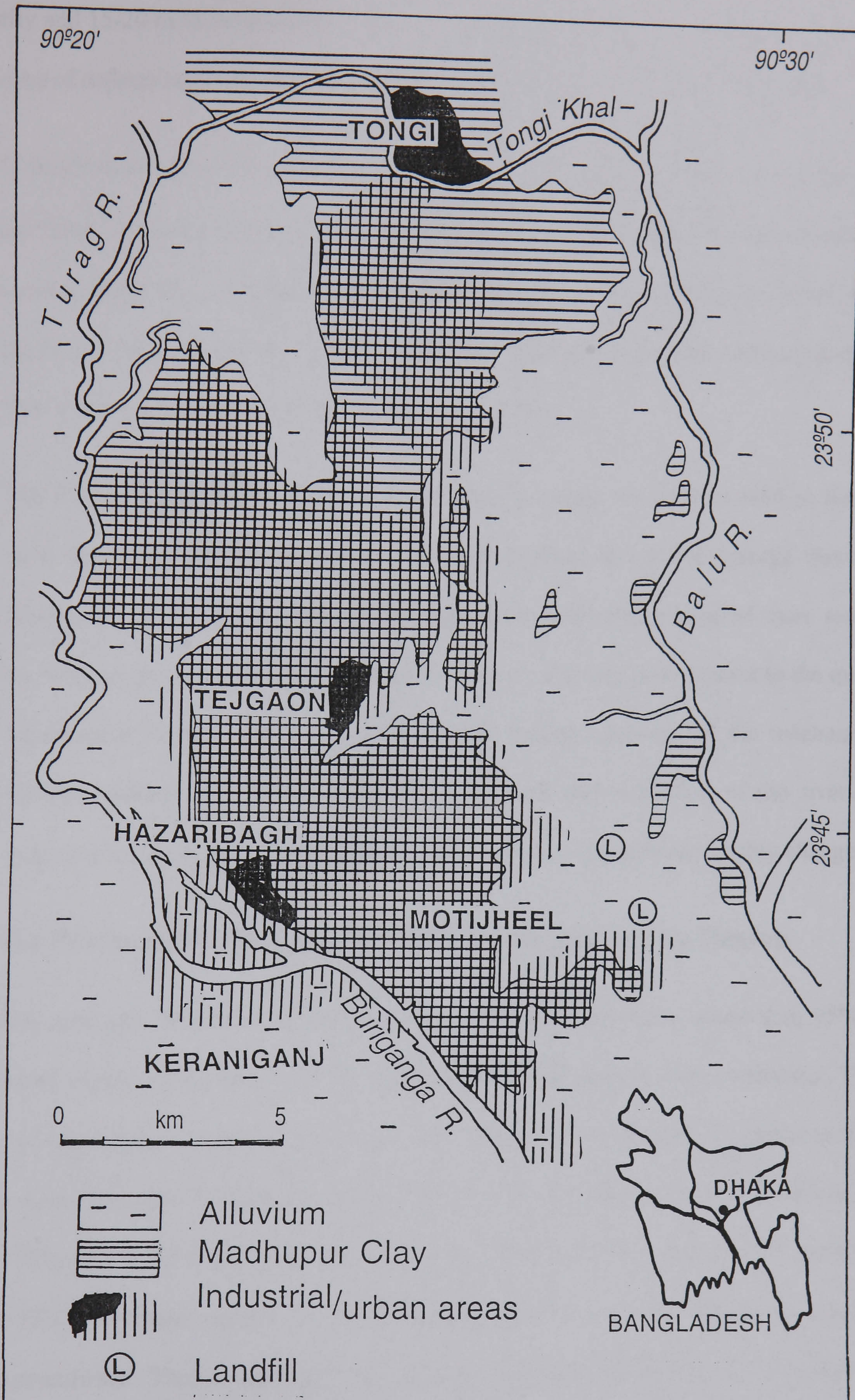


***Figure 1.3** Dhaka: urban area and surface geology*

city and 15-20 m in the periphery. The average rate of piezometric decline is 1 m/year. The cone of depression extends towards the rivers bounding the city in every direction.

Groundwater quality is also an issue. The River Buriganga is polluted by sewage and by untreated industrial wastes; concern is centred on contaminants from the chemical and tanning industries. Leachate from municipal landfills and from industrial waste disposal lagoons in the low-lying areas of the city threaten the quality of induced urban recharge. Yet little is known and hardly any monitoring is undertaken.

The future sustainability of groundwater abstraction from the aquifers will be dependent upon the ability of induced river recharge and enhanced vertical leakage through the Madhupur Clay to match the increasing groundwater abstraction. Both of these sources of recharge are polluted, though to an unknown extent, and they pose a threat to the quality of groundwater in the aquifer. This problem has focused attention on the mechanisms of induced recharge and, in particular, the assessment and modelling of the river-aquifer interaction, in order to act as a basis for predicting future groundwater quality changes.

1.4 Previous Research on the Hydrogeology of Dhaka Region

Because groundwater is so important for Dhaka city, providing more than 95% of its water supply, a number of hydrogeological investigations have been carried out. The first hydrogeological study of Dhaka city was conducted by Parsons Corporation (Welsh, 1966). The same Consultant re-evaluated the groundwater resources of Dhaka city in 1974, 1977, 1979 and 1980 (Welsh, 1974; Welsh, 1977; Parsons, 1979 and Parsons, 1980). All these reports are generalized, resource-based evaluations of Dhaka city groundwater. The Bangladesh Water Development Board (BWDB), in their water supply paper, included the Dhaka region and prepared two reports (BWDB, 1979 and BWDB, 1984) regarding the general hydrogeology of Dhaka region. In 1991, BWDB identified the over-abstraction of groundwater in Dhaka aquifer and evaluated the effects and discussed the various environmental consequences of over-abstraction (BWDB, 1991). In 1991, Engineering and Planning Consultants/Sir Mott MacDonald & Partners (EPC/MMP) carried out a detailed groundwater resources and subsidence study in the Dhaka region. This study modelled groundwater flow in the aquifer and the detailed review of this study is given in Chapter 7. The BGS (Davies, 1994) studied the geology and hydrochemistry of the Dhaka region during the International Development Authority (IDA) Deep Tube Well (DTW) II project. Much less work has been carried out on the quality of groundwater in the aquifer and in particular, on the variation in quality and level of contamination in the aquifer.

Some research work on hydrogeological conditions in Dhaka city and its adjoining areas has been carried out by MSc research students in the Dhaka University (Halim, 1980; Alam, 1985; Salahuddin, 1990; Chowdhury, 1993; Sharif, 1995), at Bangladesh University of Engineering and Technology (BUET) (Aziz, 1990; Bhuyia, 1995; Ahmed, 1986), and at Jahangirnagar University (Majumdar, 1996).

1.5 Research Objectives and Thesis Structure

The main objective of the research is to assess the vulnerability of groundwater in Dhaka city to pollution. Subsidiary objectives of the study are:

(1) To collate available data to describe the variations in time of quality of groundwater abstracted for public supply in Dhaka city;

(2) To identify the spatial and vertical distribution of groundwater quality in the aquifer;

(3) To identify the potential sources of pollution in the Dhaka aquifer;

(4) To examine the relative importance as sources of pollution to the aquifer of enhanced vertical leakage and induced recharge from the rivers;

(5) To predict the further deterioration of groundwater quality likely in the aquifer;

(6) To discuss the options/alternatives for more sustainable development and management of groundwater in Dhaka city.

Chapter 1 provides a brief introduction of the concept of aquifer vulnerability, the importance of groundwater in urban areas, the development of urban hydrogeology and the close interaction and interdependence between urbanization and groundwater development. This Chapter also includes a brief introduction to Dhaka city and the objectives of the present research.

Chapter 2 presents the environmental and urban context of Dhaka in more details, describing its topography, hydrology, water supply, urbanization, industrialization, sewage and waste disposal.

Chapter 3 and Chapter 4 describe the geology and hydrogeology of Dhaka, introducing the geological setting, stratigraphy and lithology, the aquifer system, aquifer properties, piezometry and groundwater abstraction.

Chapter 5 of the thesis presents results of a detailed inorganic hydrochemical study of the Dhaka aquifer. The data are interpreted in terms of the spatial trends and vertical profiles in the aquifer. Also, limited results of previous studies are collated to provide an indication of groundwater quality trends with time.

Chapter 6 presents the result of a reconnaissance survey of organic contamination of the aquifer.

Chapter 7 presents the development of a groundwater flow model of the Dhaka aquifer system. The model uses data from a previous model by Mott MacDonald as its basis. The model is calibrated against observed field data.

In Chapter 8 the groundwater flow model is used as a basis for development of a solute transport model in the Dhaka aquifer system to test the *relative* importance of different sources of contamination to the aquifer and to predict the future quality deterioration of groundwater in the city aquifer.

Chapter 9 contains a summary of the contributions of the thesis and includes discussion, conclusions and recommendations regarding the vulnerability and management of the Dupi Tila aquifer in Dhaka city.

CHAPTER 2 THE DEVELOPMENT OF URBAN DHAKA AND ITS ENVIRONMENTAL CONTEXT

2.1 Climate

Dhaka has a subtropical, monsoon climate. This is marked by cool and short winters, and long and hot summers with heavy monsoon rainfall. Relative humidity is high, and active wind speed is low. Temperature ranges between 30^0C and 40^0C in summer whereas the minimum average temperature during winter is 9^0C. Average annual rainfall is about 2100 mm (BBS, 1995). Monthly rainfall and evaporation of Dhaka city are shown in Figure 2.1.

Winters (November to February) are mainly dry. Rainfall is rare and the minimum temperature may drop to about 5^0C. The humidity is relatively low and skies are generally clear.

In summer (March to May) Dhaka is hot, wet and very humid. During this time the higher temperatures occasionally exceed 40^0C and are accompanied by frequent violent thunderstorms and winds ranging up to 90 km/hr. The monsoon or rainy season extends from May to October and 90% of the rainfall occurs during this season. Storms are of high intensity and some have duration of several days. Cyclonic storms with destructive winds are frequent during both the early and the late stages of the monsoon season.

2.2 Topography and Surface Water Drainage

Dhaka city is situated at the southern limit of the fault-bounded elevated terraces which form the Madhupur Tract. The terraces are raised above the surrounding floodplain, slightly undulating and moderately dissected with a low internal relief.

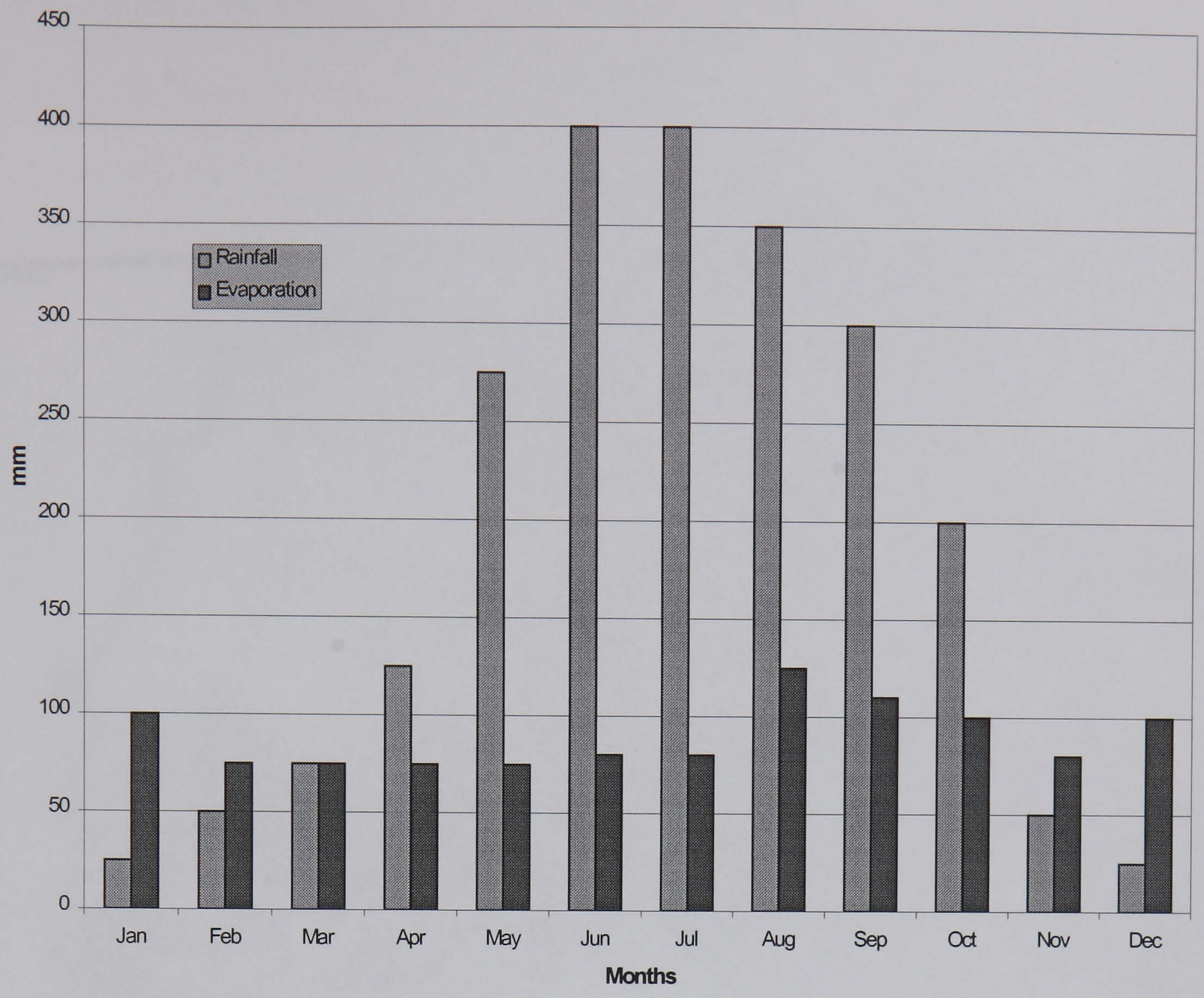


Figure 2.1 Monthly rainfall and evaporation of Dhaka city, averaged 1970-1996 (data from BBS, 1996)

The tributaries of the Turag, the Buriganga and the Balu river dissect the Dhaka region. Due to the effect of dissection and erosion numerous rounded and elongated hillocks occur. This pattern is reflected in the topography of the city which is characterized by low relief with many isolated depressions. The general slope of the land is from north to the south and southeast, in which direction the ground surface merges with the recent floodplains of the River Buriganga. To the east and west there is a similar gradation from the Madhupur Tract Terrace surface to the floodplain of the Turag and Balu rivers respectively.

The surface elevation of the city ranges from 1.5 to 15 m above the PWD datum (Figure 2.2), with an average elevation of 6.5 m (Umitsu, 1985). The elevation of the Madhupur

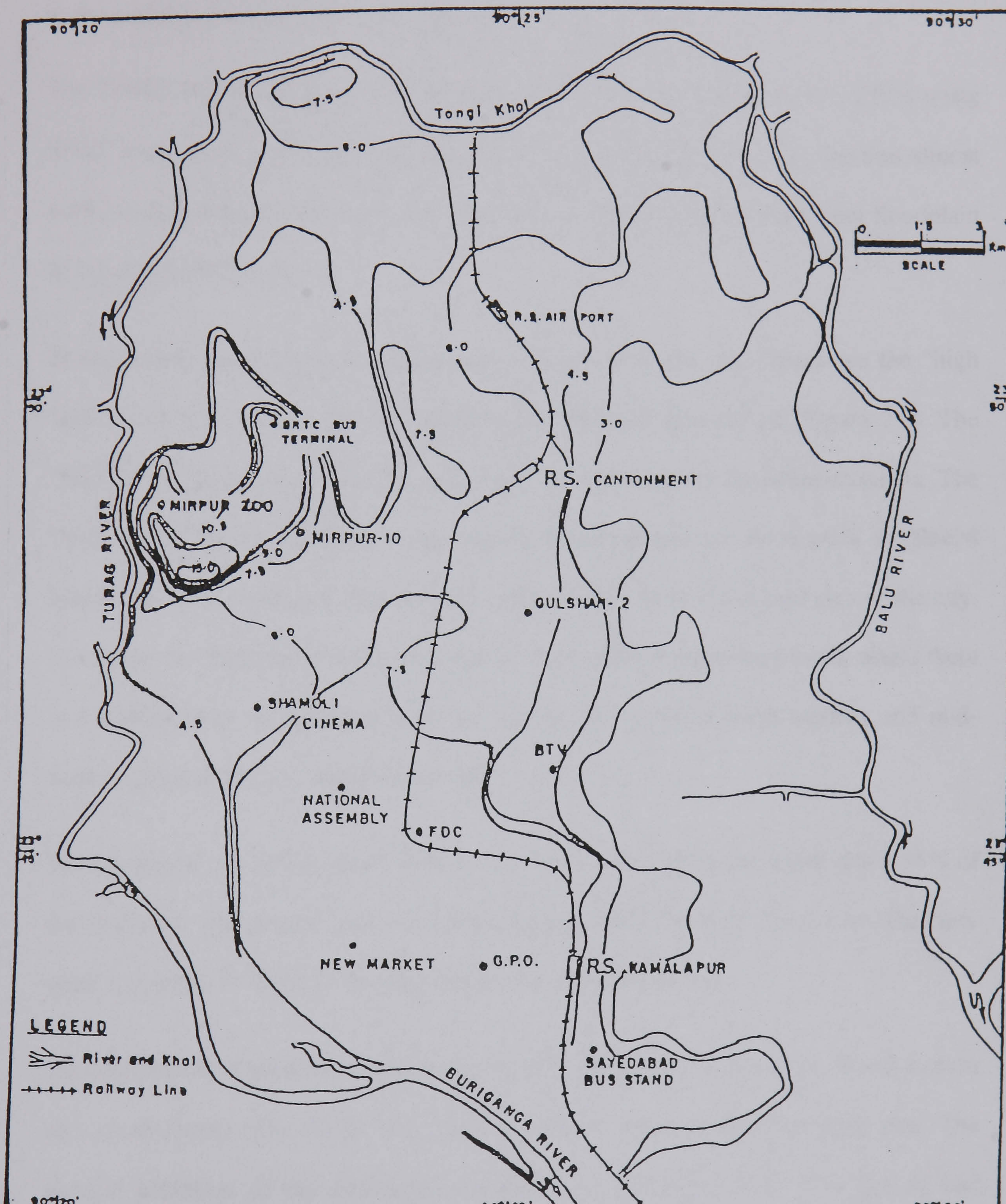


Figure 2.2 Topography of Dhaka city (contoured in m above PWD) (after Umitsu, 1985)

Tract terraces ranges from 5 to 15 m; the city has spread in places onto the lower ground of recent floodplains which do not exceed 1.7 m elevation (Asaduzzaman, 1996). The maximum elevation is in the northwest part of the city and the minimum elevation occurs in the peripheral areas of the city respectively.

The Dhaka region has been classified geomorphically by Asaduzzaman (1995) using SPOT images and geological and soil maps. The central parts of the city form an almost north-south trending inlier which projects through the alluvium of the recent floodplain in the surrounding areas.

Three distinct landforms can therefore be recognized in the city. These are the "high lands", the "low lands", and the abundant channels and depressions (Figure 2.3). The "high lands" stand above the floodplain and are traversed by abundant channels. The "high lands" are elongated in a north-south alignment and are surrounded by fluvial landforms of recent origin. They occupy approximately 40% of the land area of the city. Normally the "high lands" have an abrupt contact with the recent landforms where there is a sudden drop of elevation by a few metres. The extreme north-western and mid-western parts of the city are highly eroded.

The peripheral part of the city is built on the "low lands" which constitute about 35% of the city area. The general ground surface elevation of this unit is 3 to 3.5 m. The "low land" is usually affected by flooding during the monsoon season.

Depressions and abandoned channels are found in the north-western, central and eastern and south-eastern part of the city. They constitute about 25% of the land area. The general elevation of the abandoned channels and depressions is 1.5 to 2.5 m and sometimes they lie below the normal flood-level. Elsewhere they have been termed

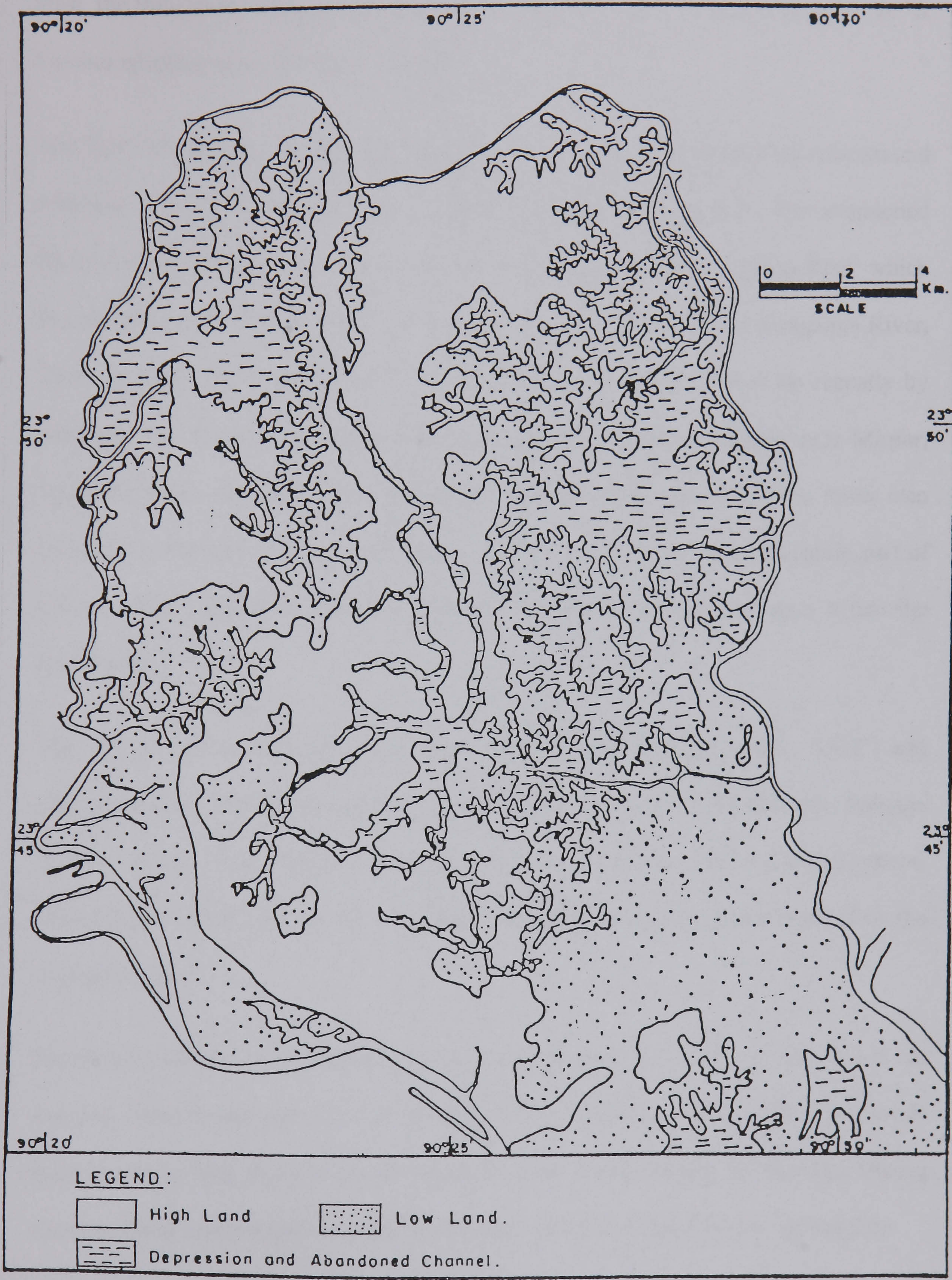


Figure 2.3 Landforms map of Dhaka city (after Asaduzzaman and Nasreen, 1990)

“recent landforms” (Assaduzzaman and Nasreen, 1990). Rivers surround the city of Dhaka on all sides: the Buriganga river to the south and southwest, the Turag river to the west, the Balu river to the east and the Tongi river to the north of the city (Figure 2.4). A number of other water channels transect the city.

The River Buriganga, branching off from the Dhaleswari, comes through the western and southern side of the city and again joins the Dhaleswari at Fatullah. The abandoned lower part of the Buriganga used to be a small stream known as the ‘Dholai Khal’ which flowed through the middle of the city until recently. The mouth of the Buriganga River, where it used to take off from the Dhaleswari River, has been choked up recently by siltation. The Turag River comes from the north and joins the Buriganga near Mirpur, being the major tributary of the Buriganga for most of the year. The Balu River also comes from the north and joins the Lakhya River near Demra in the southeastern part of the city. The Tongi River takes water from the Turag River and discharges it into the Balu River.

The city is traversed by numerous small streams (with the local name “khal”) and elongated lakes. These form tributaries to the main rivers in an overall dendritic drainage pattern. The drainage channels in the western part of the city exhibit a trellis pattern. Most of these small streams, lakes and khals are seasonal, poorly drained and fed by the monsoon water.

Flooding in Dhaka city is almost a regular annual event. Every year the depressions are flooded. Flash floods aggravate the intensity of the flood hazard. Generally, river levels start to rise in May and the flood reaches its peak during August /September. During October flood levels begin to recede. Some areas of very low land may be perennially

Figure 2.4 Drainage map of Dhaka city (after SoB, 1955)

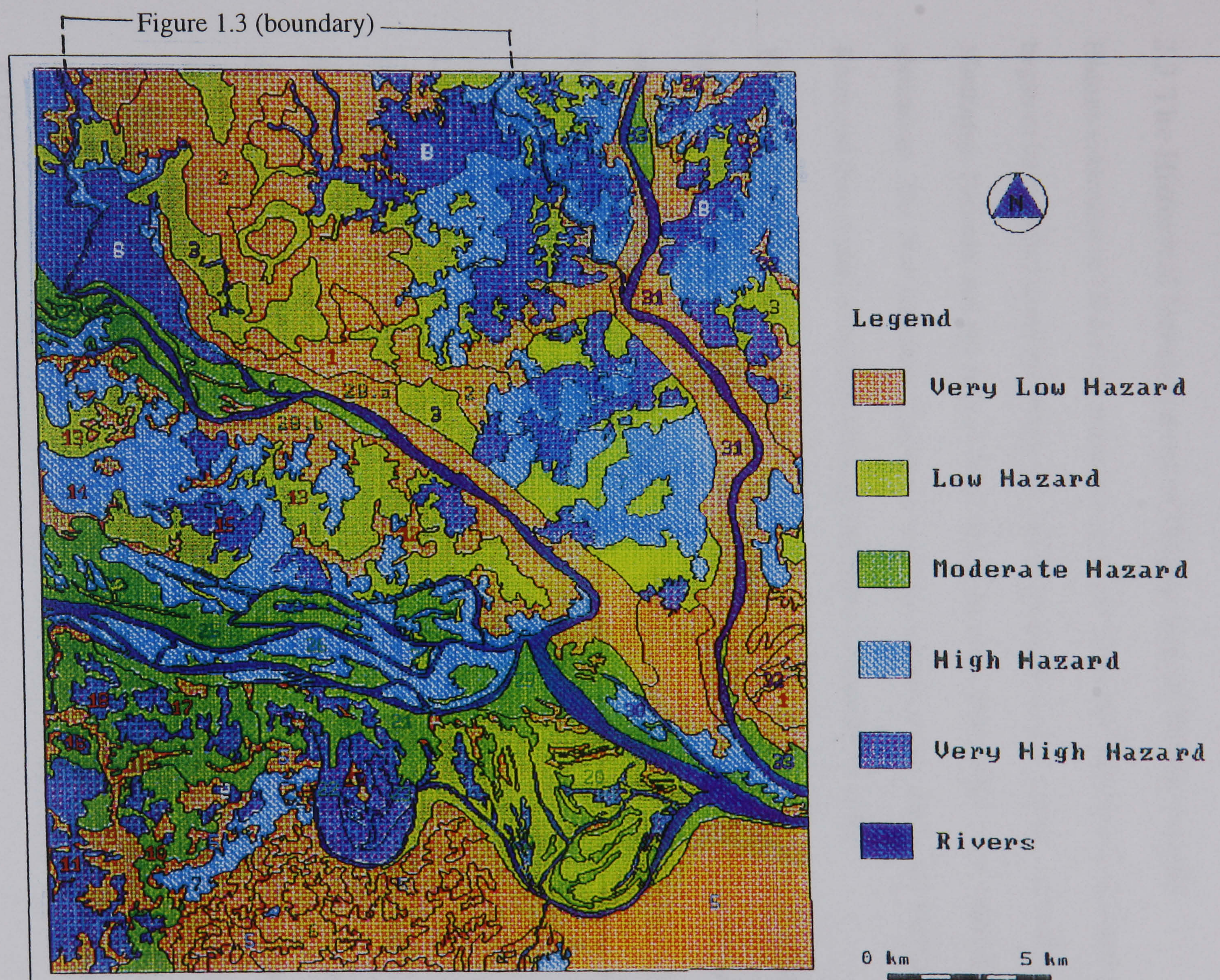


Figure 2.5 *Flood hazard zonation map of Dhaka region (from Asaduzzaman, 1996)*

flooded. However in the "high land" areas covered of the Madhupur Tract flooding only occurs in extremely wet years. Recently a flood hazard zonation map of Dhaka region has been prepared using GIS mapping (Asaduzzaman, 1995) (Figure 2.5). This illustrates the areas with low, high and very high flood hazard in the region.

2.3 The Historical Development of Dhaka and its Water Supply

Human settlement in Dhaka city started around 1100 years ago and the natural landform began to be modified about 800 years ago. Initially only the higher ground, especially the Madhupur Terraces and the natural levee along the river Buriganga, were selected for settlement. The first settlement began on the high natural levees along the Buriganga River and then expanded towards the high Madhupur Terrace in the north.

Dhaka has a long history as a regional capital due to its strategic and commercial position at the head of the Bay of Bengal, at a point on the River Buriganga where the slight elevation of the Madhupur Tract gives some protection against flooding. Four hundred years ago in the pre-Mughal period Dhaka was restricted to an area of 1.5 km^2 at the junction of the Buriganga and 'Dholai Khal'.

Dhaka became the capital of the Mughal viceroys at the beginning of the 17th Century, and a centre for their expansion of overland and maritime trade. Islam Khan Chisti transferred the capital here from Rajmahal and renamed it Jahangirnagar after the name of the reigning Mughal Emperor Jahangir (1605 - 1627) (Dani, 1962). With the decline of Mughal power in the 18th century began the period of the British Rule (1764 - 1947). At the end of the 19th century the Chadnighat Water Works were constructed on the River Buriganga to provide water for Dhaka, which became the capital of the East Bengal and Assam Province in 1905.

At the time of partition of India when Dhaka became the capital of East Pakistan it had expanded to cover an area of 40 km^2. In 1949 the Department of Public Health Engineering drilled the first borehole in the city, initiating groundwater development for public water supply. By the 1960s groundwater was the principal source for public supply. In 1963 the Dhaka Water Supply and Sewerage Authority (DWASA) was established and by 1966 groundwater abstraction was 30 Mm^3 per year, with surface water providing less than 10 Mm^3.

The independence of Bangladesh in 1971 stimulated an enormous increase in the development of groundwater. At that time the city population was less than two million and groundwater abstraction was less than 50 Mm^3 per year. By 1991, 150 public supply (PS) boreholes, up to 180 m deep, managed by Dhaka Water and Sewerage Authority (DWASA) and distributed across the city, were yielding a total of 170 Mm^3 per year for 6 million people. At that time the private abstraction was at least 40 Mm^3 per year, from 200 boreholes concentrated in Hazaribagh and Tejgaon industrial areas in the city. Current abstraction is closer to 270 Mm^3 per year from 220 public supply boreholes. There is a wide gap between actual demand and water production. The present status of private abstraction is not known fully but the amount might have increased during the past 7 years. Water demand is increasing at up to 5% per year. The current population of Dhaka city is nearly 10 million, and it is increasing at more than 6% per year (BBS, 1995). Dhaka is expected to be home to 18 million people by the year 2015. Trends in population and groundwater abstraction are shown in Figure 2.6.

After the independence of Bangladesh in 1971, the expansion and development of Dhaka increased rapidly. This expansion of Dhaka extended to abandoned channels and depressions. Undulating Madhupur Terraces in the north and east were partly levelled; and infilling activities in the low-lying areas became an essential factor of urbanization. The city is now expanding rapidly in every direction, having a centre in the downtown

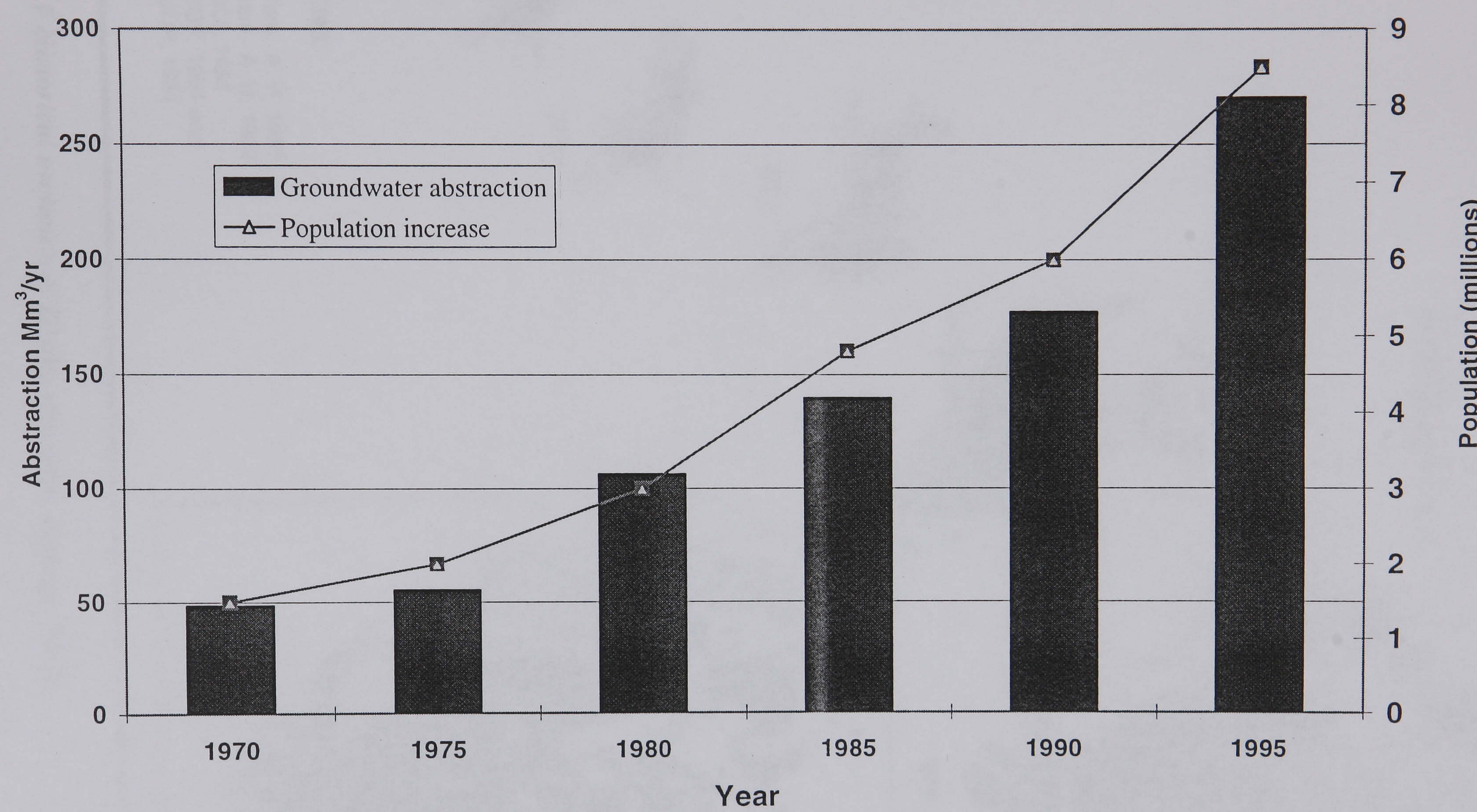


Figure 2.6 Population and groundwater increase in Dhaka city

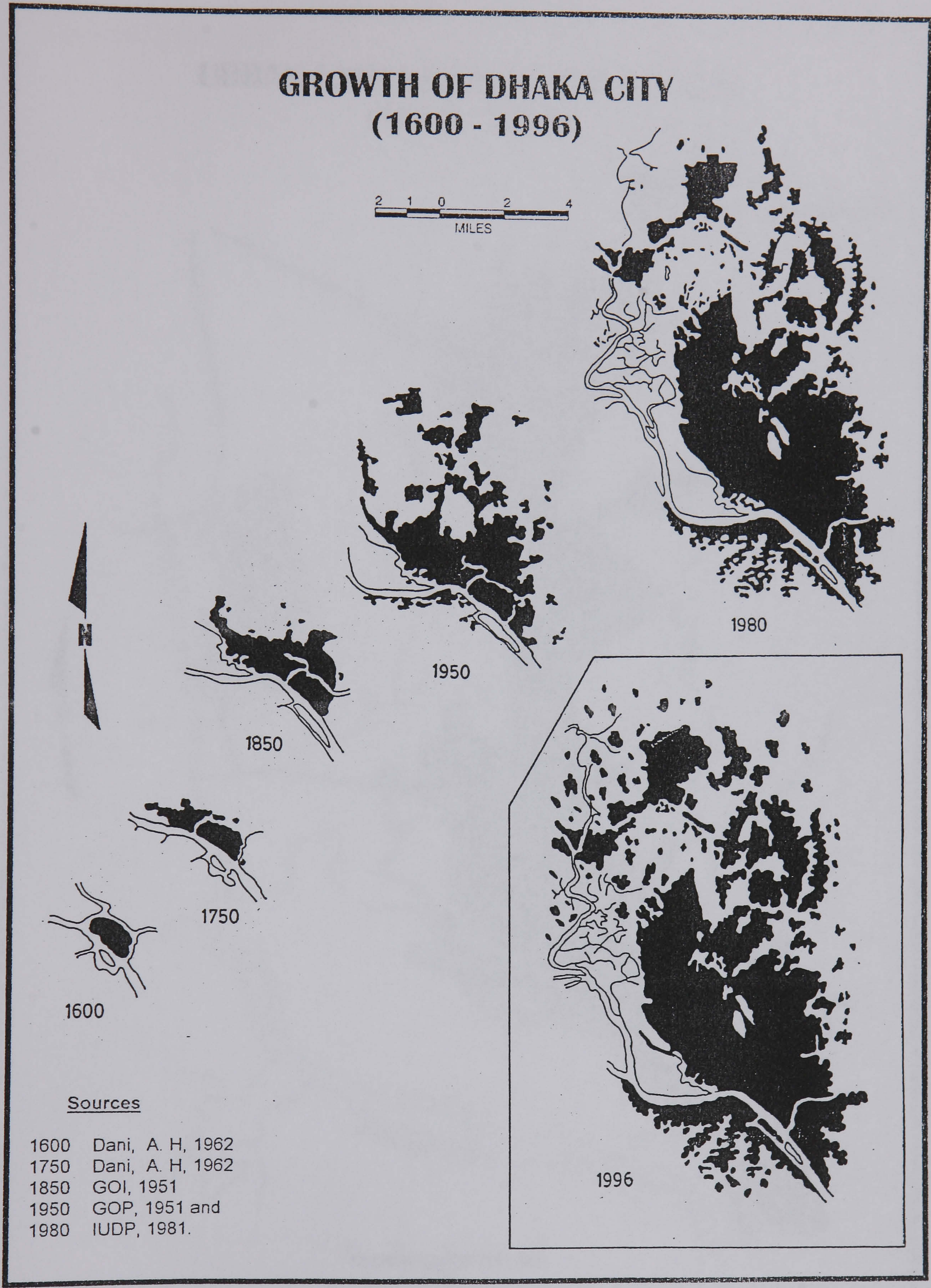


Figure 2.7 Historical evolution of Dhaka city (after Hassan, 1997)

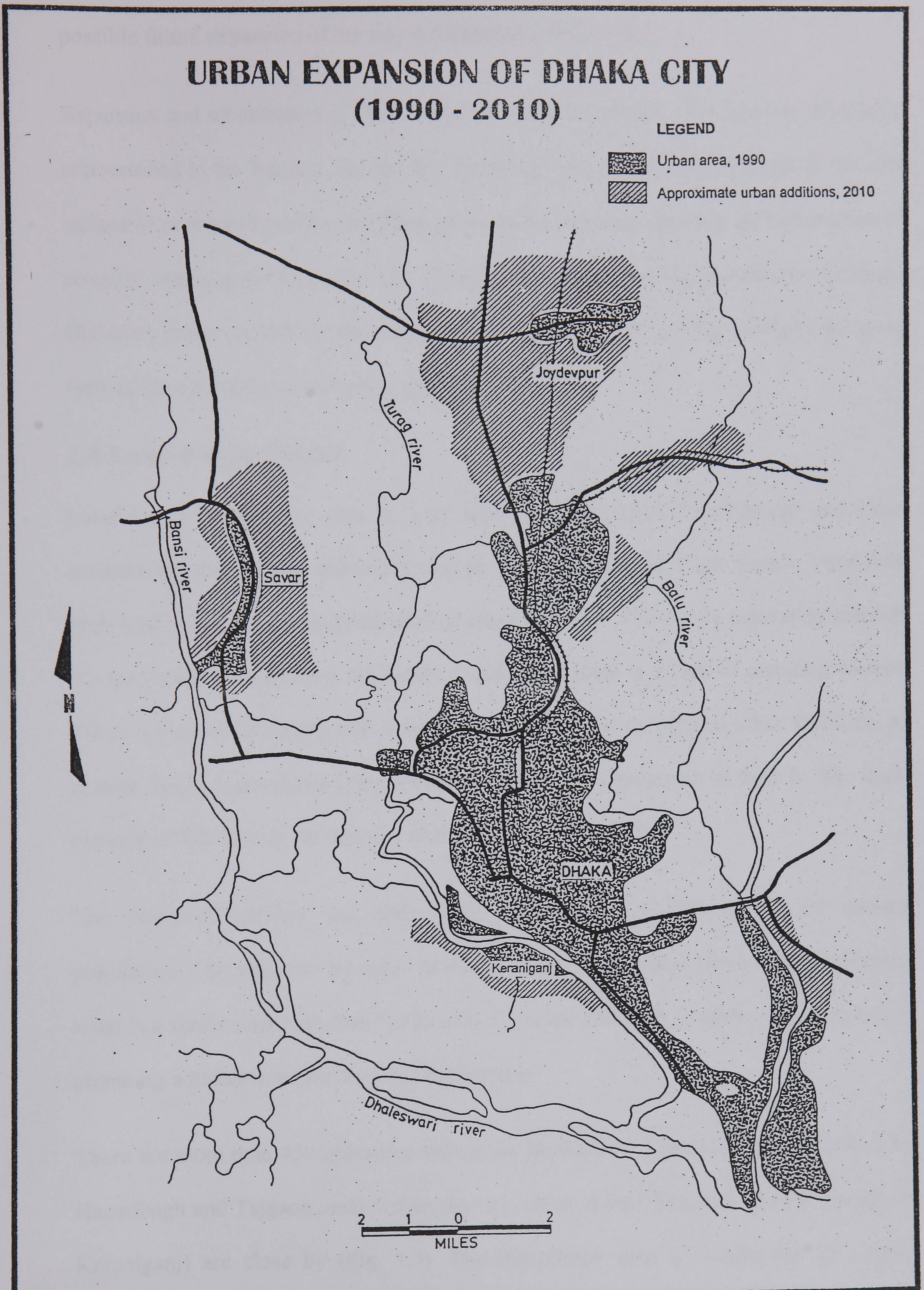


Figure 2.8 Possible future expansion of Dhaka city (after Hassan, 1997)

area. The growth of Dhaka city from 1600 to 1996 is shown in Figure 2.7 and the possible future expansion of the city is illustrated in Figure 2.8.

Expansion and urbanisation of Dhaka have been accompanied by development of industry concentrated in the Tejgaon, Hazaribagh, Keraniganj and Tongi areas. Changes to the land surface have resulted, principally filling of the natural drainage channels and construction of concrete and bituminous pavements. These effects tend to reduce groundwater recharge. However, extensive leakage from both water distribution and sewerage systems increases recharge as a continuous source throughout the year.

2.4 Land-Use in Dhaka

Land-use in Dhaka city area is both urban and industrial. Government and other autonomous and private authorities occupy the major part of "high lands". Very little high land is left for public residential or other purposes. The city is expanding towards the low-lying areas to meet the public demand, yet there is a lack of planning control. These areas are developing with very narrow roads and with minimal urban facilities. At present these occupied low-lying areas form the largest component of the city. The land-use map of Dhaka city for the year 1995 is shown in Figure 2.9.

The city road network and other urban facilities are insufficient for the present population. The city development authority (RAJUK) has developed some residential areas but these meet less than 0.1% of the demand. RAJUK is also in the process of preparing a master plan for the city development.

There are more than 450 industries within the Dhaka city. Most are concentrated in the Hazaribagh and Tejgaon areas within the city. Other industrial locations (e.g. Tongi and Keraniganj) are close by (Fig. 1.3). The Hazaribagh area is notable for its tannery industry. The textile, pharmaceutical, and chemical industries are concentrated in the

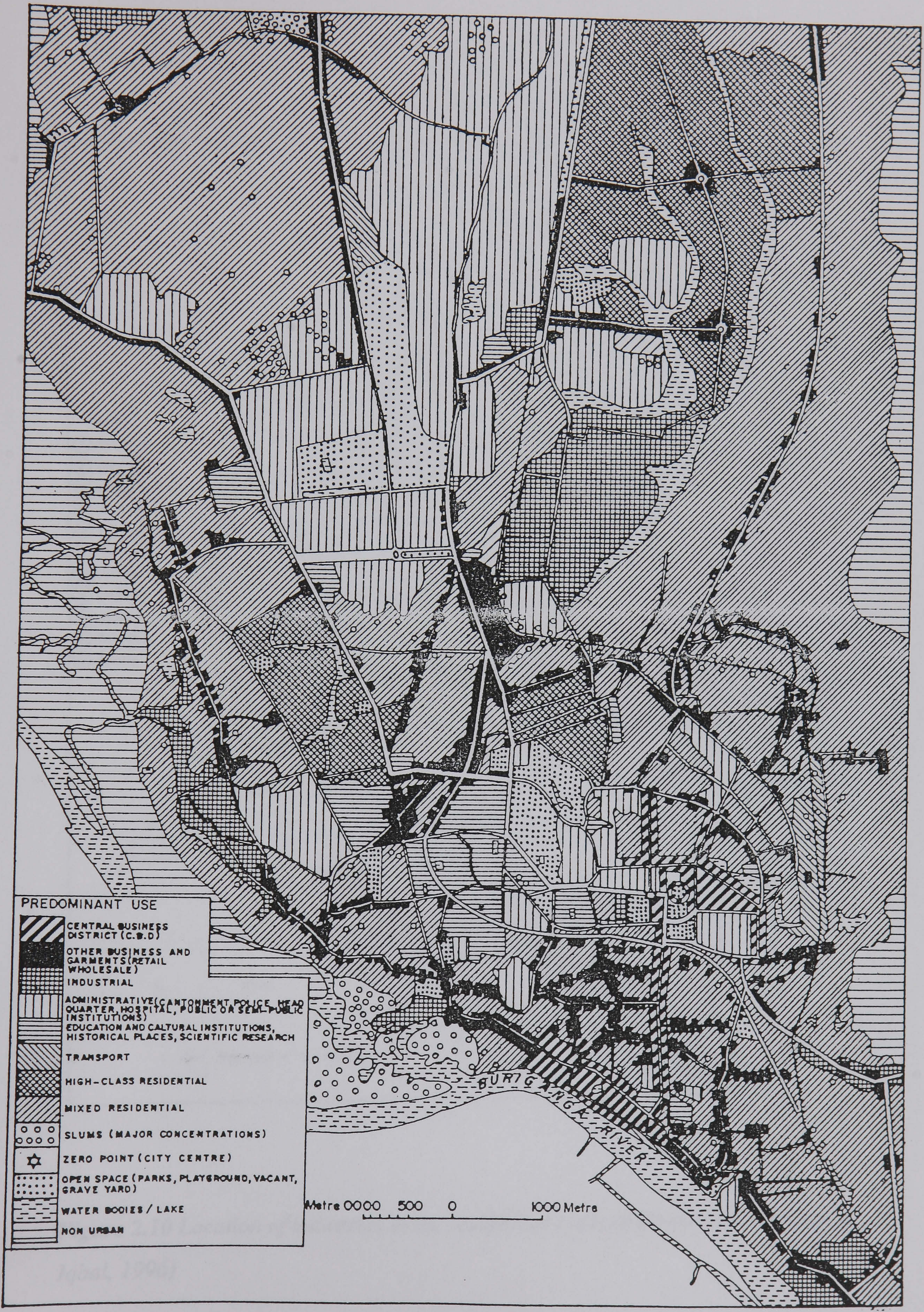


Figure 2.9 *Land use map of Dhaka city, 1995 (from Islam, 1996)*

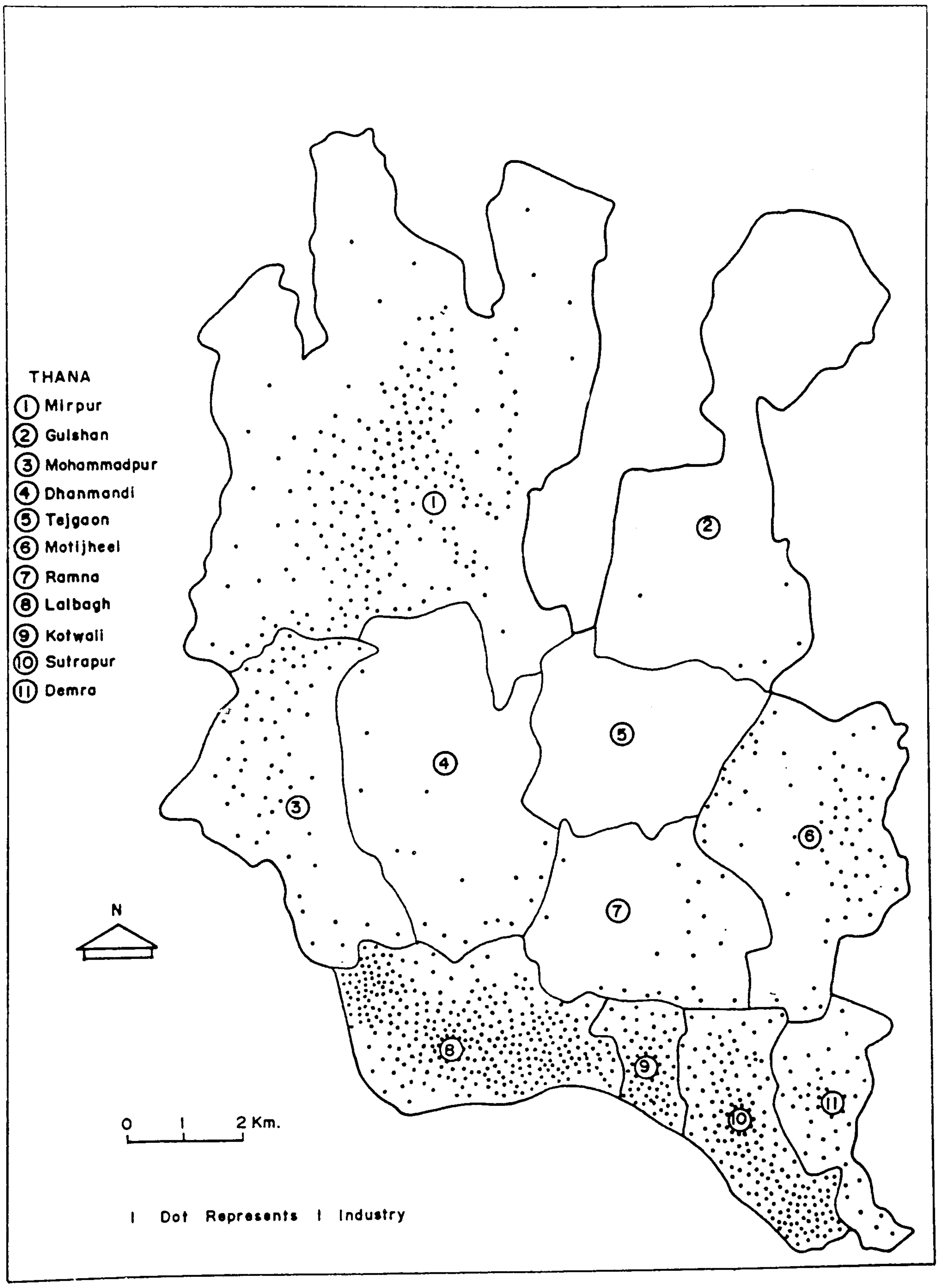


Figure 2.10 *Location of industries in the residential areas of Dhaka city, 1994 (after Iqbal, 1996)*

Tejgaon area. Small-scale industrial activities are scattered throughout the residential areas of the city (Fig. 2.10).

2.5 Sewage, Municipal Waste Collection and Disposal in Dhaka

In Dhaka, a sanitary sewage scheme was installed in 1920. Until 1920, the only major drainage was the Dholai Khal and its branches, running through the city centre and discharging its contents into the River Buriganga. All the drains were above ground, dug in the earth and were difficult to clean. During the rainy season they overflowed and affected neighbouring houses and areas whereas in the dry season they formed stagnant water bodies which were the favourable breeding place for mosquitoes and flies. By 1940, the total length of underground sewerage had been extended to 33 km (Rahman, 1989).

The present sewage system of Dhaka city covers almost the entire old part of the city and a considerable part of the new Dhaka. Due to the general flatness of the city, the sewage flows by gravity from a lift station where it is lifted by pumps about 8 to 12 m and then again flow by gravity to the next lift stations until it reaches the treatment facility at Pagla. Then from the treatment facility the effluent is discharged to the River Buriganga. The sewage system of the southern part of Dhaka city is shown in Figure 2.11. The 'Pagla Sewage Treatment Plant' was constructed in 1978 and until now it is the only treatment facility for entire Dhaka.

The general practice of garbage disposal in Dhaka city is to collect the refuse materials from the dustbins to dump them in specified landfills both inside and outside the city. The garbage of the city can be classified into the following categories (Rahman, 1989).

(i) Households refuse (ii) Commercial refuse (iii) Community refuse (iv) Factory and industrial refuse and (v) Personal refuse

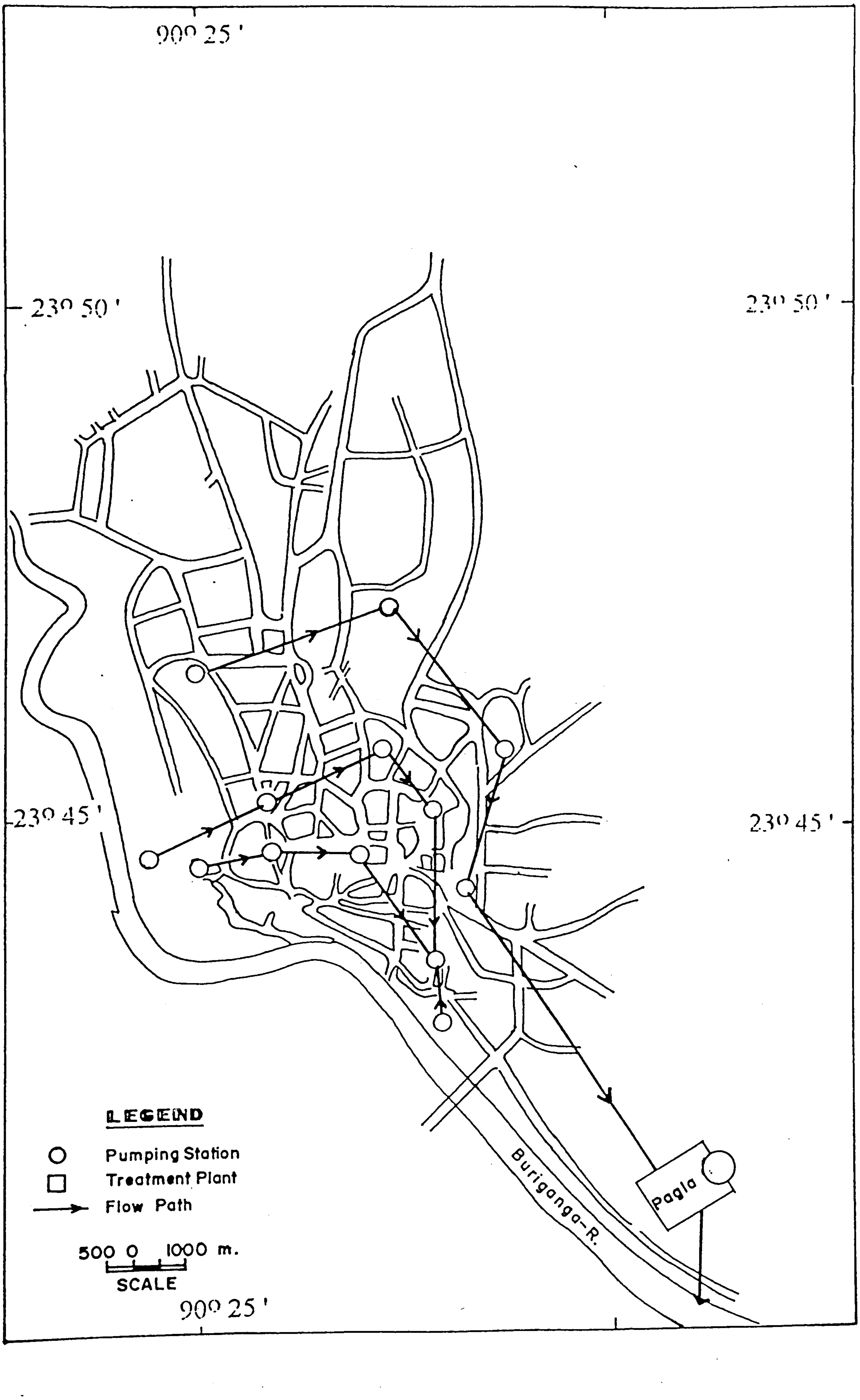


Figure 2.11 Sewage system in the Southern part of Dhaka ctiy (after DWASA, 1995)

There is no proper landfill management system in Dhaka. There has also been an inevitable rise in waste production. The Dhaka City Corporation (DCC) consigns up to 3000 tonnes of solid waste per day (including 500 tonnes domestic waste) to unlined landfills located in low-lying regions in the northwest and southeast of the city. On completion the landfills are given a thin covering of soil and become areas designated for construction. Drainage of surface water has been disrupted as the small natural channels ('khals') and low-lying areas have been infilled, often with municipal waste. The authority is filling up some depressions in the city with solid wastes. Construction of an earth Flood Protection Embankment in 1990 has resulted in blocking of the khals that remain and frequent water - logging of the surface by contaminated water.

A variety of wastes pose potential hazards: from the tanning, dyeing, metal-working and engineering industries, from solid industrial and domestic waste disposal, and from fuel spillages along the length of the river particularly in the port area where rapid expansion has taken place.

2.6 Potential Sources of Contamination of Groundwater

Development of Dhaka city immediately over the aquifer that supplies its drinking water inevitably raises the risk of pollution. The pollution of groundwater in Dhaka city arises either from point sources such as industrial locations or from a multitude of point sources such that the whole of an aquifer is subject to contamination by diffuse pollution whose exact source is impossible to identify. The potential sources of pollution in groundwater of Dhaka city can be categorized as follows:

Landfill sites and municipal wastes

Contamination of groundwater by landfills is a concern throughout the world. The primary concern associated with landfills is the production of leachate, a contaminant soup which can leave the site and pollute both ground and surface water resources. The high number of cases of groundwater pollution at old landfills with no measures to control leaking into the groundwater support the concern of leachate entering the groundwater (Christianson *et al.*, 1994). On average about 3000 tonnes of solid waste is dumped by Dhaka City Corporation (DCC) everyday in some selected places of Dhaka city. More than 85% of this waste is dumped at Mugdapara dumping site (Plate 2.1a) and the rest is dumped elsewhere sporadically like Rayer Bazar, Kazla, Jatrabari (Plate 2.1b) and at other places. The unlined and uncontrolled landfills pose a serious threat to groundwater beneath Dhaka city. The climatic condition of Dhaka is favourable for percolation of rainfall through the landfill and the leachate will penetrate the subsoil and pollute the shallow groundwater. There is no provision for leachate and landfill gas management nor monitoring; it is not surprising that the little data available close to the Mugdapara landfill (Ahmed *et al.*, 1995) show that shallow groundwater is polluted by leachate. In addition, the mixing of industrial wastes with domestic wastes in landfill sites of Dhaka city poses an additional threat to its groundwater. Chemical analyses of groundwater from various landfill sites are given in Chapter 5. Municipal wastes produce toxic and carcinogenic chlorinated hydrocarbon solvents (CHSs) which have been found to contaminate groundwater in many urban areas of the world. However, with the limited analyses of groundwater samples in and around the landfill sites of Dhaka to date no CHSs have been found. A detailed description of these analyses is given in Chapter 6.

Industrial Pollution

Some of the most serious cases of groundwater contamination are reported in urban centres with a long history of industrial activity. Industry stores, uses and produces a wide range of organic and inorganic chemicals, and it is inevitable that at least some of this material will eventually enter the sub-surface, with the potential to degrade groundwater quality. Untreated industrial effluents are discharged to rivers, low-lying and swampy areas and

Plate 2.1a Mugdapara landfill (Dumping site)

Plate 2.1 b A swampy area in Jatrabari is being filled by Municipal Wastes

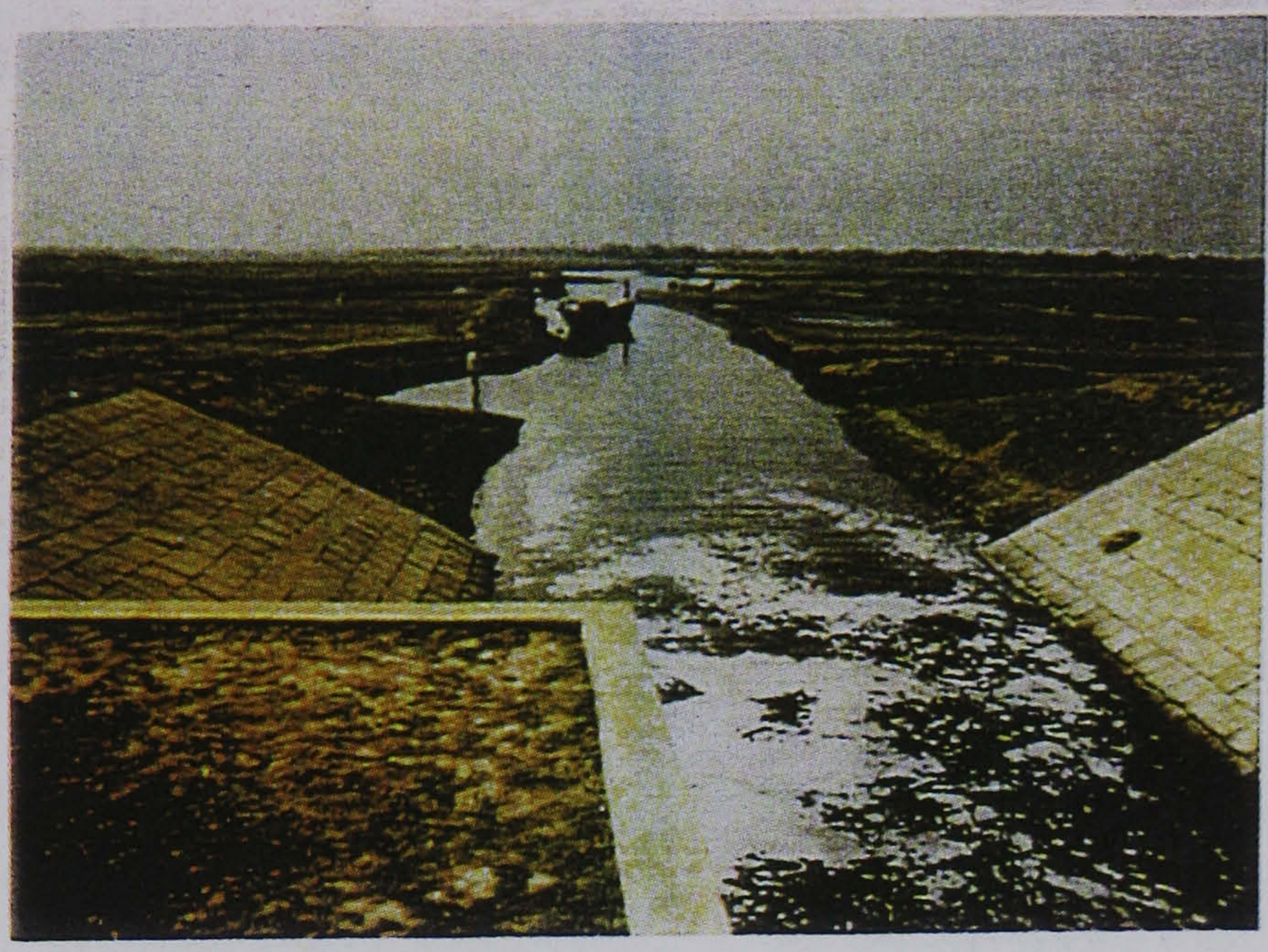


Plate 2 2a Leachates of Hazaribagh 'Khal' are channeled to the river Buriganga

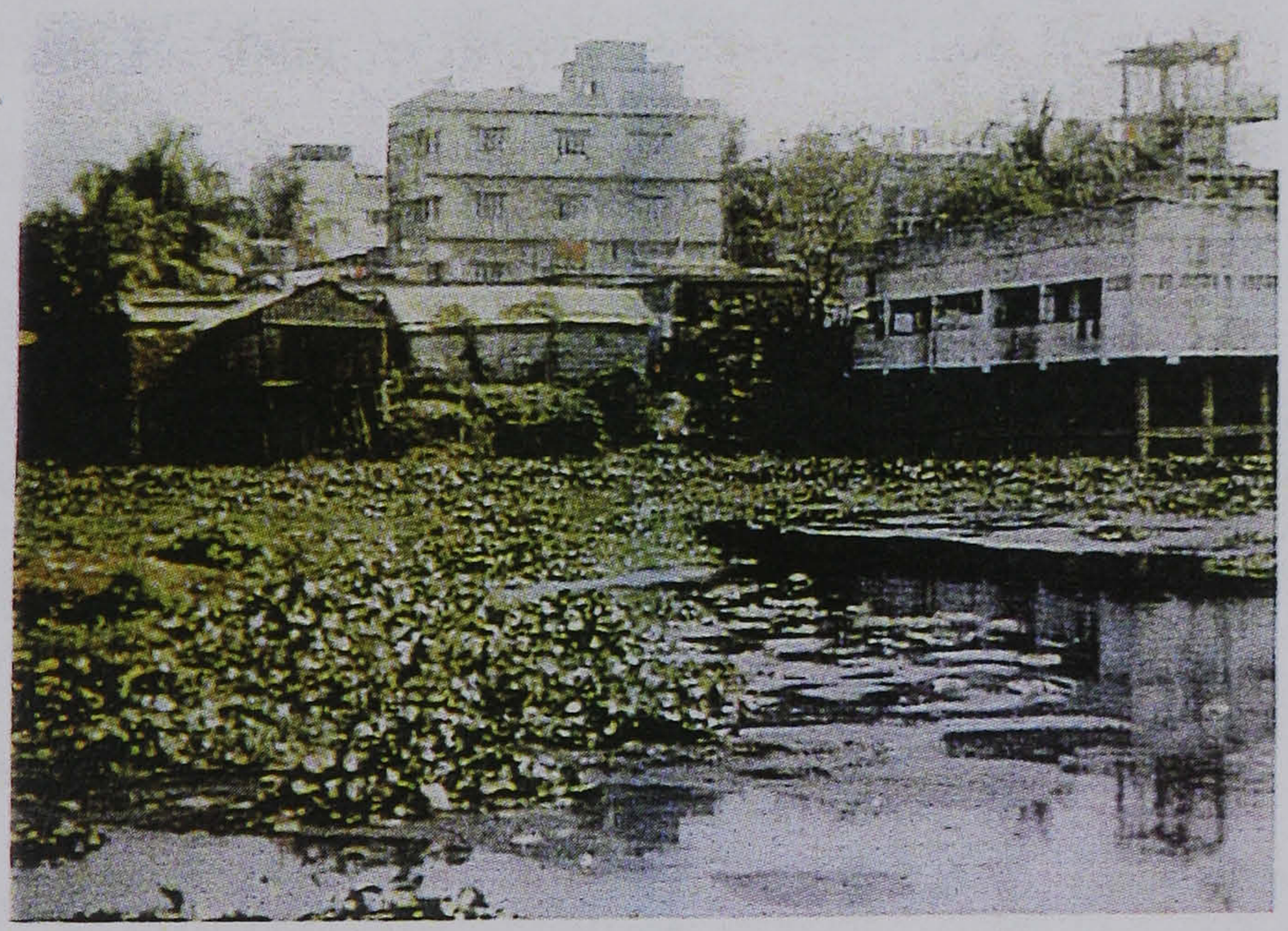


Plate 2.2 b *Leachates produced during the monsoon within the city*

surface water bodies in and around the city. Typical examples of such dumping sites are 'Begun Bari Khal' at Tejgaon Industrial area and 'Hazaribagh khal' (Plate 2.2b) and Buriganga River at Hazaribagh tannery area. The main drain taking industrial effluent, sewage and storm runoff to the River Buriganga, monitored by the Department of the Environment, is grossly polluted. Sewage is also channeled by a large number of open-drains throughout the city area towards the River Buriganga and to surface water bodies such as Gulshan Lake.

Industrial wastes generally result in heavy metal pollution (both of land and groundwater) and there is some evidence of such land pollution in the city (Ullah, *et al.*, 1995). Analysis of groundwater samples from different depths in the Hazaribagh area is discussed in Chapter 5. The impact of the effluent and polluted river water is shown to be more pronounced in shallow groundwater as compared to deep groundwater in Chapter 5 (also Ahmed *et al.*, 1999 and Burgess *et al.*, 1999).

The most severe threat comes from toxic organic chemicals that are sufficiently soluble, mobile and persistent in water to migrate some distance from their source and enter wells, surface streams and lakes. Organic contamination of urban groundwater by industrial effluent is severe and widespread (Pankow *et al.*, 1996). A reconnaissance has been made of the organic contamination of groundwater in Dhaka city as part of this research and the results are described in Chapter 6.

Leakage from Sewage Line and Septic Tank

Most studies of sewer pipe leakage have concerned the groundwater quality in many cities in the world. Septic systems are also used worldwide for the disposal of wastewater. Geochemical conditions in the soils and sediments commonly fail to provide the degree of natural attenuation necessary to adequately treat the liquid effluent. Leakage from sewage lines and septic tanks is a common problem in Dhaka city. It is evident that the causes of elevated nitrate in urban groundwater are poor sanitation, septic tank leakage, open drains etc. All these conditions prevail in Dhaka city and the trend is increasing with time. These conditions are also responsible for microbiological pollution of groundwater in Dhaka city.

Polluted Surface Water

The changes in the groundwater flow system can redirect poor-quality water in some areas toward pumping centres (Alley, 1989). The rivers surrounding Dhaka city are sites for indiscriminate disposal of municipal and industrial wastes which may contaminate the city groundwater. The river Buriganga is particularly important in this regard. The Buriganga is polluted by industrial and municipal wastes, tannery effluents and sewage. Due to the changing hydraulic condition the Dupi Tila aquifer receives direct recharge from the Buriganga riverbed. The elevated EC value of groundwater along the riverbank may be caused by recharge with polluted water from the Buriganga.

Hydrocarbon Related Pollution

Hydrocarbon fuels and oils (LNAPLs) leaking from above ground and underground storage tanks represent one of the greatest threats to the quality of urban soil and groundwater because they are so widely stored in urban areas (Francois and Molyneux, 1997). There are hundreds of filling stations, automobile workshops and underground storage tanks within the Dhaka city. These tanks and waste disposal reservoirs in the city are subject to structural failure so that subsequent leakage becomes a source of groundwater pollution. This is particularly very true for a city like Dhaka where these structures are operated without any proper control. In addition, the spillages of hydrocarbon in the river Buriganga by a huge number of river vessels make the river water filthy. This hydrocarbon polluted river water can contaminate the aquifer by induced recharge.

2.7 The Impact of Urbanization on the Groundwater Environment

Urban development of Dhaka stresses its groundwater resources by increasing demand, changing the rate and distribution of aquifer recharge, and introduces contaminants that can seriously degrade its water quality. The urban growth of the city has profoundly changed the groundwater balance in the city. Both the quantity and quality of groundwater resources in Dhaka are being threatened by urban growth and associated industrial development. The change in land-use pattern by construction of roads, buildings, embankments, pavements, airport runways may reduce the recharge rate. In addition, present land development practices by filling of natural depressions and canals in and around the city may also reduce the natural recharge significantly. However, leakage from water supply mains and sewers, on-line sanitation and others form important additional components of recharge which are currently unknown.

A primary concern of urban development of Dhaka is the introduction of contaminants that can seriously and irreversibly degrade its water quality. The increasing contaminant loads are directly responsible for huge contaminated lands in the city area. The impacts of urban pollutant sources on surface water quality are well known and well documented for the Dhaka city. However, the impacts of urban pollutants on groundwater are considerably more serious and complex. Due to huge abstraction of groundwater in Dhaka city, polluted urban recharge contributing to vertical leakage through the Madhupur Clay may be partially responsible for the degradation of groundwater quality in the city. The movement of pollutants in the subsurface is generally slow and the impacts are frequently not recognized until several decades following pollutant release. The impact of urbanization on inorganic and organic quality of Dhaka city groundwater is discussed in Chapter 5 and Chapter 6.

CHAPTER 3 GEOLOGY OF DHAKA REGION

3.1 Regional Geological Setting

The study area comprises a part of the Bengal Basin, one of the deepest sedimentary basins in the world. The Bengal Basin covers an extensive area of the Northeast part of the Indian plate, which includes Bangladesh and parts of the adjacent Indian states of West Bengal, Tripura and Assam. The landward portion of the basin is located at the head of the Bay of Bengal, and is bordered on the west by the outcropping Pre-Cambrian rocks of the Indian shield, on the north by the Precambrian Shillong massif and on the east by the Folded belt of the Indo-Burman ranges (Figure 3.1). The southern limit of the basin is uncertain. However, the three mighty rivers- the Ganges, the Brahmaputra and the Meghna - have formed a very large deltaic sedimentary complex which extends south into the Bay of Bengal as the Bengal Deep Sea Fan, the largest submarine fan in the world (Curray and Moore, 1974; Curray, 1994).

The Bengal Basin has two major tectonic elements-the western and northwestern stable shelf (Indian platform), and the Bengal Foredeep. The Bengal Foredeep is divided by "the Barisal Chandpur High" (the Meghna Fault Zone) into the folded flank in the east and the platform flank (the Bengal exogeosyncline) on the west. It is within the platform flank that the study area within the Dhaka region is located. The platform flank extends from the Shillong plateau to the Bay of Bengal and contains the Sylhet trough, the Faridpur trough, the Hatia trough and the Madhupur High, which are widely believed to be bounded by faults delimiting blocks of uplift and subsidence (Morgan and McIntire, 1959; Desikacher, 1974; Khandoker, 1987; Khandoker, 1989) (Figure 3.2).

The transition zone between the Bengal Foredeep and the Indian Platform is marked by gravity and magnetic anomalies and is known as `Hinge Zone' (Sengupta, 1966; Alam,

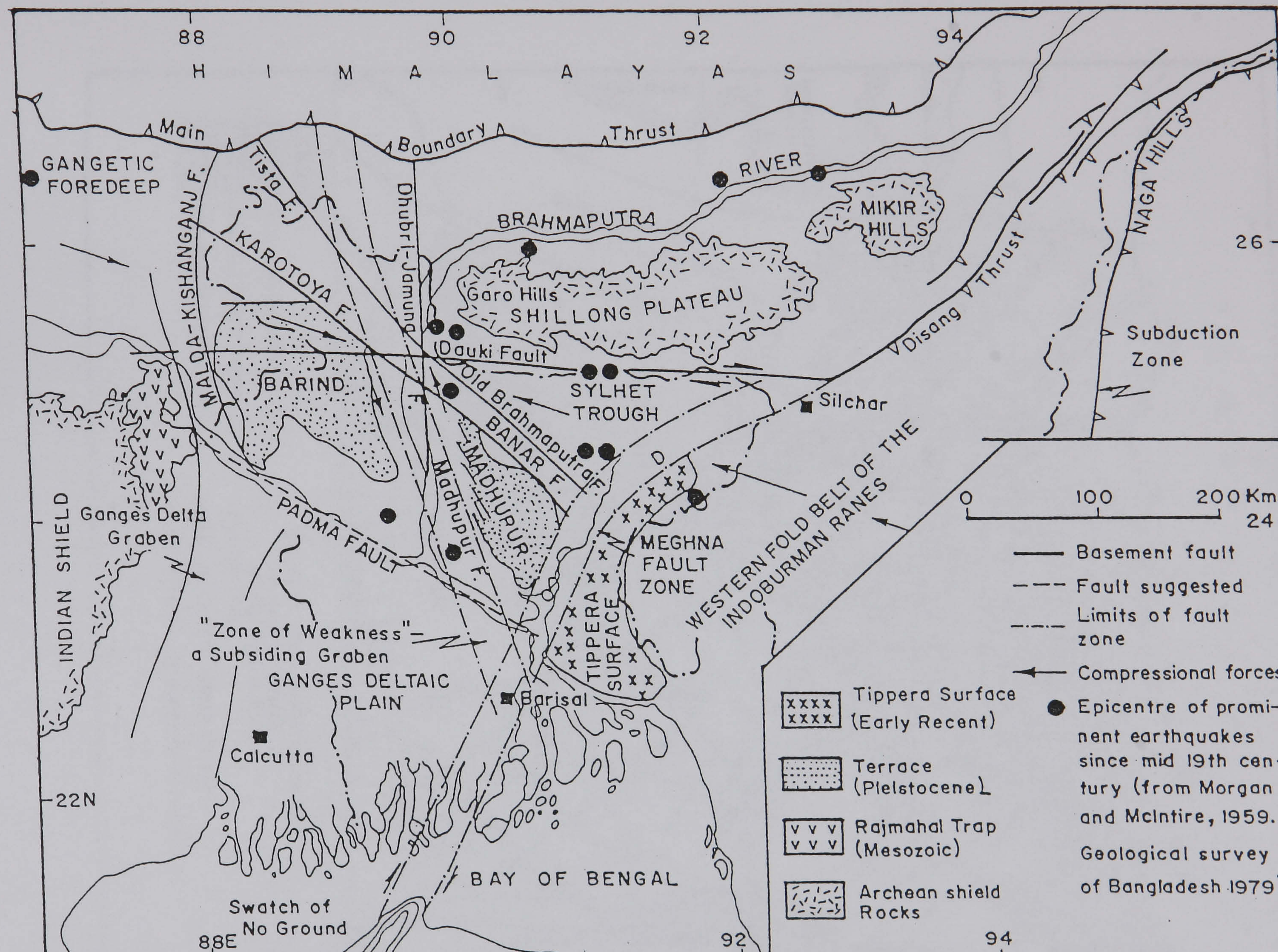


Figure 3.1 Regional geological and tectonic setting of the Baring-Madhupur areas (after Khandoker, 1987)

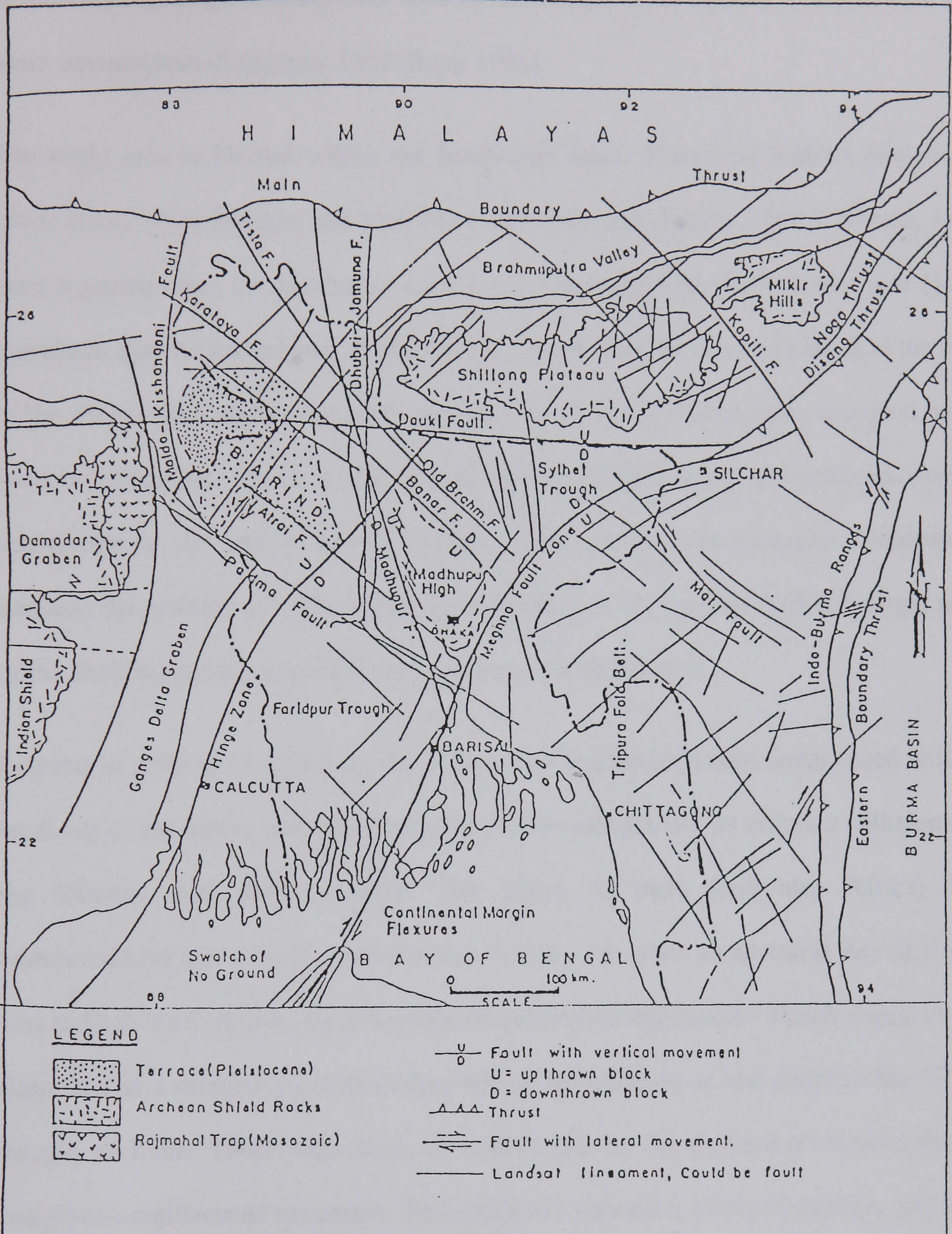


Figure 3.2 Structural features of the Bengal Basin (after EPC/MMP, 1991)

1972;). This `Hinge Zone'; believed to correspond to the Late Mesozoic Indian coast (Khandoker, 1989), is characterized by a relatively rapid increase in sediment thickness of individual geological formations with facies changes from shallow water shelf to deep basin environment (Sengupta, 1966; Raju, 1968).

The study area is located within the Madhupur Tract. Numerous authors (Fergusson, 1863; Hirst, 1916; Morgan and McIntire (1959) Mia and Bazlee, 1968; Coleman, 1969) have suggested that the Madhupur Tract is a recently uplifted block. Khandoker (1987) postulates that the Barind and Madhupur Tract were elevated as a horst block at the close of the Pleistocene, and subseqently separated by an active graben, now occupied by the Jamuna floodplain. Uplift of the Barind and Madhupur areas was compensatory to subsidence of the Sylhet Trough, Ganges Deltaic Plain and Gangetic Foredeep. In between the actively subsiding lower Brahmaputra Valley and the Sylhet Trough, uplift of the Shillong plateau may represent an isostatic readjustment.

In terms of plate tectonic theory, the evolution of the Bengal Basin commenced with the break-up of the Indian peninsula from the Gondwanaland and its ultimate collision with the Tibetian and Burmese plate. The rifting of India (and also Africa) from Gondwanaland was actually started in Pre-Tertiary age when an ancestral Bay of Bengal was formed. At that time, the Pre-orogenic calcareous-argillaceous flysch sequence was deposited as a miogeosynclinal wedge, which lies adjacent to and parallels the NE-SE margin of India. These sequences are represented by the Cretaceous-Eocene marine, calcareous-argillaceous sequences. Following the formation of the Himalayas and Indo-Burman Ranges in the early Oligocene, deltaic sedimentation was initiated in the Bengal Basin, more particularly in the Bengal Foredeep (Salt *et al.*, 1985). Lindsay *et al.* (1991) noted that the delta-building activity actually started at the break-up of the Gondwana. The post-Oligocene sediments are a regressive, post-orogenic molasse sequence.

The eustatic sea level fluctuations and tectonic activity during the Quaternary were also very significant in the depositional setting of the study area, which is outlined in Section 3.4 below.

3.2 Stratigraphy and Lithology

A generalised Cenozoic stratigraphy of Bangladesh is given as table 3. 1. The Madhupur Clay is the oldest exposed sediment in Dhaka city. It unconformably overlies the Dupi Tila Formation and is itself overlain by the Alluvium Formation of the Buriganga, Turag, and Balu rivers. A summary of the Pliocene to Recent stratigraphy of the Dhaka region is given in Table 3.2. The Dhaka region straddles the floodplain of the rivers Buriganga, Turag, and Balu, and the Madhupur Tract, and the stratigraphic table is subdivided accordingly. A stratigraphic succession of the Madhupur area proposed by Monsur (1990) is given in Table 3.3 for comparison.

It is supposed that underlying the entire region is the Girujan Clay Formation. The Girujan Clay Formation is not exposed, nor penetrated by drilling, but is inferred from its extensive occurrence elsewhere in Bangladesh. Descriptions of individual formation in terms of lithology, age and origin are given in some details in the following paragraphs.

3.2.1 Girujan Clay Formation

Evans named the Girujan Clay formation in 1932, the "type" locality being the bed of the small Girujan stream at Digboy in Assam (Evans, 1932). In Assam the Girujan Clay Formation predominantly consists of mottled and blue clay and sandy clay with subordinate sandstone. Due to a small degree of compaction, the clay becomes claystone and shale in Bangladesh. The Girujan Clay has a maximum thickness of about 1220m in Sylhet, and was possibly deposited in a lacustrine environment. The formation is of local extent due to periods of erosion prior to deposition of the Dupi Tila Formation. The

Table 3.1 Generalized Cenozoic stratigraphy of Bangladesh (From Khan, 1991)

Period		Epoch	Group	Formation
Quaternary		Holocene		Alluvium
		Pleistocene		*uconformity* Madhupur Clay St. Martin's Limestone
TERTIARY	**NEOGENE**	Pliocene		*uconformity* Dihing
		Late Miocene		*uconformity* Dupi Tila Claystone Dupi Tila Sandstone
		Middle Miocene	Tipam	*uconformity* Girujan Clay Tipam Sandstone
		Early Miocene	Surma	*uconformity* Boka Bil Bhuban
	PALEOGENE	Oligocene	Barail	*uconformity* Renji ? Jenam ? *uconformity*
		Late Eocene Middle Eocene	Jaintia	Kopili Shale Sylhet Limestone
		Early Eocene to Paleocene		Tura Sandstone

Table 3.2 Stratigraphy of Dhaka region

Age	**Stratigraphy**	**Lithology**	**Thickness (m)**
The Floodplain			
Holocene	Floodplain	Alluvial silt, sand & clay	10-100
Late Pleistocene to Holocene	Dhamrai Formation[1]	Alluvial sands	100-120
Pre-Pleistocene	Unknown	Unknown	Unknown
The Madhupur Tract			
Recent	Lowland Alluvium	Swamp, levee and riverbed sediments	<8
Holocene	Bashabo Formation[2]	Sand (discontinuous)	15-20
Pleistocene	Madhupur Clay Formation	Silty clay and sand	10-18
Plio-Pleistocene	Dupi Tila Formation	Fluvio-deltaic sand (fine)	25-40
		Dupi Tila claystone	0-8
		Fluvio-deltaic sand (coarse)	120-140
Miocene	Girujan Clay	Blue Clay	Unknown

[1] Davies (1994) and MMI (1992), [2] Monsur (1990)

Table 3.3 Stratigraphy of the Madhupur area (from Monsur, 1990)

Chronostratigraphy: Series	Chronostratigraphy: Sub-stage / Series	Formation	Member	Bed	Lithologic description	Thickness
HOLOCENE	Sub Atlantic	Basabo Silty-Clay	Matuail Clay	Silty clay	Pale olive (5Y 6/4) very sticky silty clay with modern soil on top	5
					Unconformity	
	Sub Boreal			Clayey silt	Light yellowish brown (10 Y R 6/4) very sticky clayey silt, containing plenty of plant roots and iron concretions	
					Unconformity	
	At-lantic		Gulshan Sand	Silty clay	Yellowish red silty clay	
					Unconformity	
	Boreal			Clayey silt	Pale yellow (5Y 7/3) clayey sitt, containing wood fragments, plant roots and iron conceretions	
					Unconformity	
	Pre-Boreal			Sand	Light bluish gray (5B 7/1) sand-silt-clay to sand. It contains plant roots, wood fragments and iron concretions	
					Unconformity	
PLEISTOCENE	Middle	Madhupur Clay and Sand		Kalsi bed 1	Plale yellowish brown with light brown spotted sandy clay	2
					Unconformity	
	Lower			Kalsi bed 2	Yellowish brown silty clay, containing iron concretions	4
					Unconformity	
			Dhaka Clay		Red (2.5YR 4/6) with reddish yellow (7.5 YR 6/6) spots. It is highly weathered, containing iron concretions, pipe stems, calcareous nodules, plant roots and manganese spots	5
					Unconformity	
			Mirpur Silty Clay		Light brown (5YR 4/6) sandy clay to clayey sand with moderate reddish brown (10R 4/6) spots, containing iron concretions, piope stems, plant roots and manganese spots	4
					Unconformity	
			Bhaluka Sand		Pale yellowish brown (10YR 6/2) silty sand to sand with light brown (5YR 5/6) reduction spots. It is highly micaceous and cross bedded. It contains some intraformational clayey beds	4
					Unconformity	
PLIOCENE		Dup Tila			Quartz chalcedony gravel bed Oxidized sands with intraformational clay beds. It contains large silicified wood fragments.	

Miocene Girujan Clay rests conformably on the Miocene Tipam sandstone but a pronounced unconformity marks its upper contact with the overlying Dupi Tila Formation.

3.2.2 Dupi Tila Formation

The Dupi Tila Formation was named by Evans (1932) after its occurrence at a hill of that name half-way between Sylhet and Jaintiapur in the northern part of the Surma Basin. The Dupi Tila Formation has the most widespread occurrence of any Cenozoic Formation in Bangladesh. The formation extends across almost all Bangladesh, outcropping in most of the areas of the hilly regions of Sylhet, Lalmai and Chittagong Hill Tracts, or overlain by a relatively thin mantle of Holocene alluvium (Khan, 1991).

The Dupi Tila Formation is generally subdivided into two units, a lower sandstone and an upper claystone unit, separated by an unconformity at least in the Surma Basin. (Hiller and Elahi, 1984). The maximum thickness of the sandstone is 914 m whereas the overlying claystone is more than 1,800 m thick in Sylhet. The Dupi Tila sandstone is a yellow, medium to coarse grained, massive ferruginous sandstone. It is poorly consolidated and contains quartz granules and pebbles with subordinate claystone. The claystone is predominantly grey, mottled plastic clay, containing occasional lignite, with subordinate siltstone and yellow, poorly consolidated sandstone.

On the basis of lithological descriptions, the sediments underlying the Madhupur Clay across the Madhupur Tracts have been ascribed to the Dupi Tila Formation (e.g. Alam, 1988 and Alam *et al.,* 1990). The sands forming the confined aquifer beneath Dhaka city are therefore assigned to the Dupi Tila Formation. Although the Formation itself is not exposed in the study area, the uppermost part is exposed in some quarries e.g. at the Mirpur brickyard, distinguished by the presence of a marker gravel layer 'the quartz-chalcedony gravel bed' which immediately overlies the formation (Monsur, 1990). The Formation is also thought to be exposed along part of the bed of the River Buriganga. In the study area the formation is mainly a sand unit with intraformational clay beds. At the top of the Dupi Tila Formation are fine silty sands which grade downwards into fine/medium-grained sands, and medium/coarse grained sands with gravels towards the base. These sands are approximately 140 m thick in Dhaka. The sands are oxidized, micaceous, yellow to yellowish grey, massive, cross-bedded, well-sorted fine to medium grained and coarse grained sands with occasional gravels at depth. They contain an appreciable amount of iron oxides and secondary clays as weathering products of the original mafic minerals throughout. The typical facies distribution and lithological variation of the Dupi Tila Formation is illustrated using the geological log of a borehole (Bhaluka 77R) drilled within the Madhupur Tract (Figure 3. 3).

Table 3.4 shows the mineralogy of the Dupi Tila sands from the Madhupur area as determined by x-ray diffraction (MMP/HTS, 1983). Quartz, feldspar and micas predominate, with subordinate kaolinite and chlorite; several other mineral species including goethite, epidote, rutile, ilmenite, ferric hydroxide and amorphous alumino silicate gel have also been identified by x-ray diffraction. Other x-ray diffraction studies conducted by Ahmed (1994) on the Dupi Tila sands from the Barind Tract confirm a similar mineralogy to these sands in western Bangladesh. The formation shows a more diverse assemblage of heavy minerals than do earlier older units, indicating variable sources of sediments (Uddin and Lundberg, 1998).

The clay lenses within the formation are kaolinitic. There are substantial amounts of grey clay and orange ferric hydroxide cements present within the Dupi Tila Formation. Mica is also present usually in a weathered orange to clear form, but wood fragments are generally absent (Davies, 1994). On the Barind the Dupi Tila sands contain 0.2% by

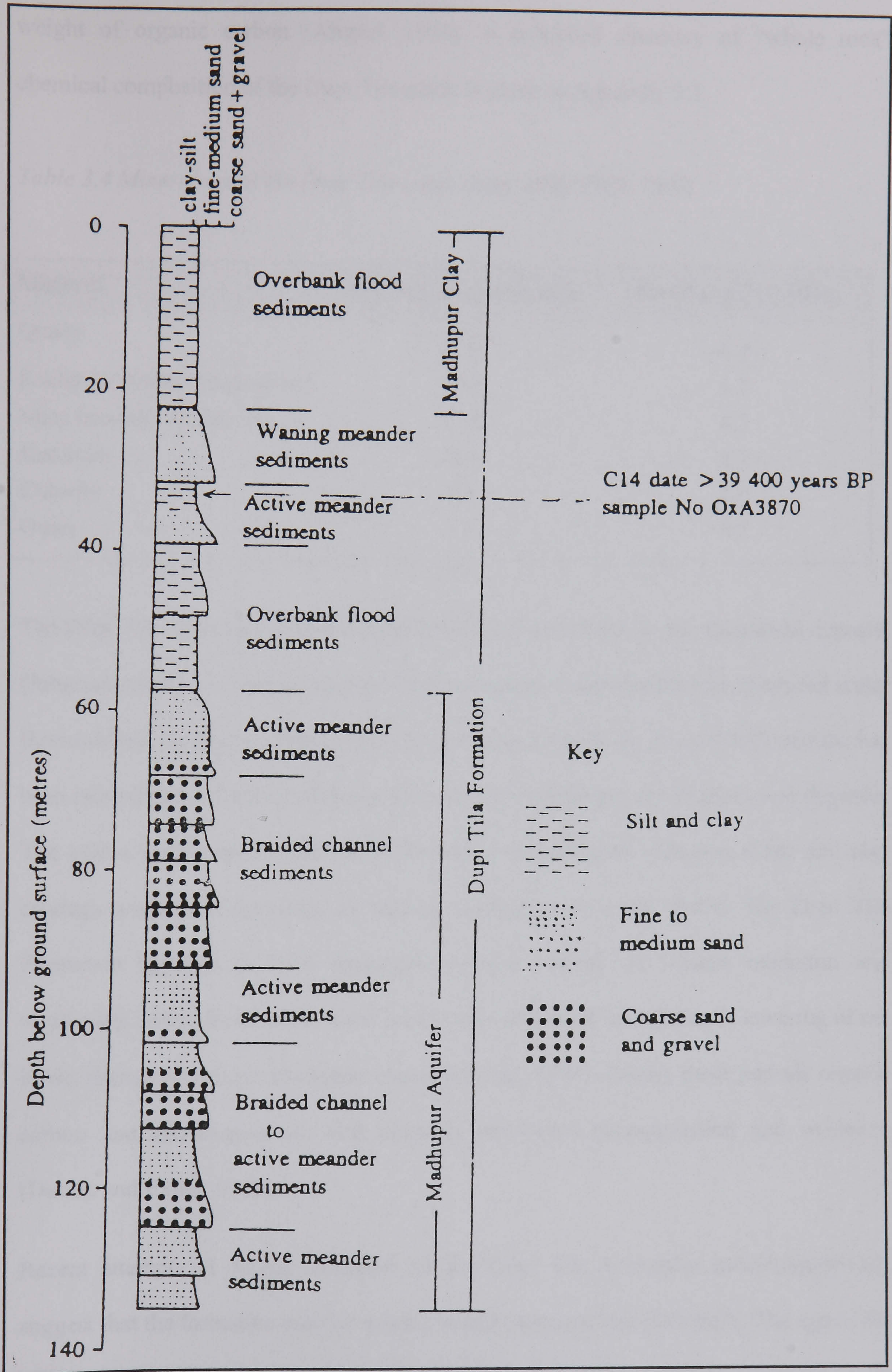


Figure 3.3 Geological log and facies distribution of the Dupi Tila Formation (after Davies, 1994)

weight of organic carbon (Ahmed, 1994). A tabulated summary of "whole rock" chemical composition of the Dupi Tila sands is given in Appendix 3.1.

Table 3.4 Mineralogy of the Dupi Tila sands (after MMP/HTS, 1983)

Mineral	Average % of minerals	Standard Deviation
Quartz	51.6	6.9
Feldspar (mainly plagioclase)	28.6	6.5
Mica (mainly muscovite)	12.0	4.5
Kaolinite	4.0	1.7
Chlorite	3.1	2.0
Other	1.4	0.5

The Dupi Tila Formation consists of alternating fluvial channels and floodplain deposits (Johnson and Alam, 1990). The Dupi Tila Formation in Bangladesh was deposited under fluvio-deltaic conditions (MMI, 1992). In Sylhet and Assam the Dupi Tila Formation has been interpreted as a series of fining-upwards active-meander and braided-river deposits. The yellow and brown colour of the formation is associated with iron oxide and clay coatings which are the result of mineral weathering as noted above. The Dupi Tila Formation appears to have undergone several periods of intense oxidation and weathering during times when water levels were depressed in response to lowering of sea levels during successive glaciation events (Davies, 1994). During these periods organic carbon and ferromagnesiam rich minerals underwent decomposition and oxidation (Davies and Exley, 1992).

Recent attempts at dating sediments of the Dupi Tila Formation paleomagnetically suggest that the formation may be much younger than previously thought. The age of the formation has been accepted as Pliocene to Pleistocene (Alam *et al.*, 1990; Reimann, 1993 and Worm *et al.*, 1998). Yet on the basis of paleomagnetic studies Monsur (1990) has given the Dupi Tila Formation a minimum age of only 900 000 years.

3.2.3 Madhupur Clay Formation

The Madhupur Clay Formation has surface exposure over more than half of Dhaka city, where its thickness varies from 6 to 25 meters, with an average of 10m. The Formation also extends some meters below the flood plain areas of the city. Similar clays on the Barind Tract and Lalmai Hills are more or less time equivalent. The term Madhupur Clay is widely used, but is poorly defined, for the tough, over-consolidated reddish-brown to grey silty clays observed across the Madhupur Tract. Recently the Formation has been renamed as the 'Madhupur Clay Residuum' by the Geological Survey of Bangladesh (GSB) (Alam *et al.*, 1990), and the 'Madhupur Clay and Sand' Formation by Monsur (1990). The age, origin and the stratigraphical position of the formation has been, and still is, disputed. Previous workers have identified the origin of the Madhupur Clay as marine (Brammer, 1971), lacustrine (Islam, 1976), deltaic (Bakr, 1977) and even glacial (Eusufzai, 1967). The current interpretation of the GSB is that the clay is a residual soil horizon produced by post-depositional weathering of feldspars in a deltaic sand sequence. The base of the clay is gradational with the Dupi Tila sands from which it has by this interpretation been derived.

On the other hand, Monsur (1990) produced a formal lithostratigraphic definition of Madhupur Clay and Sand Formation, divided into the upper clayey and the lower sandy units, with a well-defined 'quartz-chalcedony gravel' marker band at its base. He proposed that its origin as overbank flood deposits. According to Monsur, the Formation was subsequently subject to soil-forming processes, and formation of cumulative paleosols alternating with the increment of a few millimetres or centimetres of sediments by numerous minor floods in the basin. Hassan (1986) also regards the clays as a fluviatile sequence with interbedded paleosol horizons. On the basis of reversed magnetic polarity, Monsur concluded that the age of the Formation is middle to upper Pleistocene (between 730 000 and 900 000 y old).

As also described by Rizvi (1970), Islam (1976) and Alam (1988) the Madhupur Clay Formation can be subdivided into two units: the upper clay and the lower clayey sand.

The Upper Clay Unit: The thickness of the upper clay varies from less than 1 to14 m. The clay is generally brownish red to brick red. It is a plastic clay, compact when dry and soft when wet, and is intercalated with fine sand and silt. Brown ferruginous concretions occur particularly in the weathered zone of the upper part of the unit and calcareous nodules are found locally.

The Lower Clayey Sand Unit: The thickness of the lower clayey sand unit varies from 3 m to 10 m. The unit consists of grey colored sticky, plastic and compact clays with a mottling of red, brown, yellow and organic colours. Sand lenses and calcareous nodules are present. The sands are mostly quartz, fine to medium-grained and highly micaceous (mostly muscovite). The proportion of sand increases with depth towards the base of the unit, and it passes downwards into sand which is now recognised to belong to the Dupi Tila Formation.

There are no systematic published accounts of the mineralogy of the Madhupur Clay in the Dhaka region. However, the following comments may be made based on the individual reports.

Islam (1976) reported that the sand fraction of the clay is 85-95% quartz and contains less biotite than the recent alluvial sands. He also compared the bulk chemistry of the Madhupur Clay (using 8 samples) with recent alluvium (using 5 samples) and stated that on average the clay of the Madhupur Clay Formation contains more aluminium and combined water and much less calcium and magnesium than recent alluvial clay. A summary of the "whole rock" chemical composition of the Madhupur Clay is given in Appendix 3.2. Alam *et al.*, (1990) noted that the Madhupur Clay is mainly illite with minor kaolinite and alkali feldspar is more common than plagioclase. The major heavy mineral components identified are tourmaline, brown hornblende and epidote (Monsur and Paepe, 1990).

3.2.4 Dhamrai Formation

The Dhamrai Formation is a stratigraphic name recently proposed by MMI (1992) after the town Dhamrai in Dhaka district. The Dhamrai Formation, of Late Quaternary age, underlies the low-lying floodplain of the Ganges/Brahmaputra river system and its distributaries. The formation is divided into two units separated by a discontinuous paleosol horizon. The Lower Dhamrai Formation (Lower Alluvial Sequence) is a fining-upwards succession of coarse sands and gravels deposited by strongly flowing braided rivers (Davies, 1994). The coarse to medium sands of the Upper Dhamrai Formation (Upper Alluvial Sequence) were also deposited as a series of upwards fining units, from smaller braided and latterly, meandering rivers.

Radiocarbon ages obtained from analysis of wood fragments provide approximate dates of deposition of the Dhamrai Formation sediments. The basal coarse sediments of the Lower Dhamrai Formation were deposited between 20 000 and <48 000 years BP, while those of the Upper Dhamrai Formation were deposited between 7 000 years BP and the present day (Davies, 1994). It is believed that the Dhamrai Formation was formed by the infilling of incised valleys cut during the last glacial maximum.

3.2.5 Bashabo Formation

Drainage channels and shallow depressions on the Madhupur Tract are partially infilled with grey and yellow organic-rich sands and clays of the Holocene Bashabo Formation. Monsur (1990) first proposed the name and produced a formal lithostragraphic classification of the Formation. The Bashabo Formation is divided into two members: the (lower) Gulshan Sand Member and the (upper) Matuail Clay Member. The lower Gulshan Sand Member is a fining-upward sequence with light bluish-grey sand and sandy silty clay at its erosional base. This bed is overlain by yellowish clayey silt containing plant roots, wood fragments and iron concretions. The top bed is an yellowish red silty clay.

The upper Matuail Clay Member is divided into two beds. At the base it is a yellowish brown, plastic clayey silt with abundant plant roots and iron concretions. The top bed is a pale olive, plastic silty clay with a modern topsoil above. According to EPC/MMP (1991) the sediments of the Bashabo Formation (referred to by them as the Highland Alluvium) may be as much as 25 m thick in the eastern part (Rampura area) of the city where they rest directly on the Dupi Tila sands. Monsur has dated reworked wood fragments from the lowest bed of the Gulshan Sand Member at 12,780 BP. The sediments of the Bashabo Formation presumably formed by slow siltation of tributaries of the incised channels of the paleo-Jamuna and Brahmaputra. The term Bashabo Formation is basically equivalent to the Highland Alluvium of Alam (1988).

3.2.6 Lowland Alluvium

The Lowland Alluvium of Alam (1988) can be divided into three sub-units- Backswamp and Depression Deposits, Natural Levee and Interstream Deposits and Riverbed Deposits.

Backswamp and Depression Deposits: These deposits are extensively developed in the northeastern and central-eastern part of Dhaka city. They are grey to dark grey and black in colour and consist mainly of soft to firm clay and silty clay. They are massive and sticky, containing peat and wooden logs, and are up to 5m in thickness.

Natural Levee and Interstream Deposits: These are extensively developed in the east and southeast part of the city. The deposits consist of fine sand, silt and clayey silt. They are grey, massive and friable, and are up to 4-5 m in thickness.

Riverbed Deposits: Riverbed deposits occur as sandbars, point bars and bed fills developed only in the Buriganga River. The point/sand bar is also reported at the confluence of the Balu and Lakhya rivers. The sandbars are grey and yellowish grey sand and silty sand. The sand is medium to fine grained, unconsolidated and well sorted and shows current bedding.

3.2.7 Floodplains Deposits

These deposits occur throughout the recent floodplain area adjacent to the rivers of Buriganga, Balu, Tongi and Turag and mainly consist of clayey silts formed within the last 2,000 years. These sediments contain considerable amount of feldspar and mica. The mineralogy of the floodplain sediments of the Brahmaputra and Ganges rivers differs from those of the Meghna river system. Sediments of the Brahmaputra and Ganges rivers usually contain 15% to 30% of feldspar, and 5 to 30% of mica (both biotite and muscovite), and some silty beds may contain as much as 80% mica (Brammer, 1971). Thus the sediments typically contain 25 to 40% of easily weathered material. This compares with only 1 to 10% of feldspar and less than 5% of mica in the sand fractions of the Madhupur Clay (Brammer, 1971) with typically 4 to 9% of easily weathered minerals. Detailed description of the mineralogy and sedimentology of the units is available from MMI (1992). The thickness of the deposits varies from a few meters to more than 100 meters. The Madhupur Clay Formation and Dupi Tila Formation are not present on the western side of the river Buriganga within the depths currently reached by drilling (150 m).

3.3 Structure and Tectonics

Dhaka lies at the southern end of the Madhupur Tract, a fault-bounded block of Pleistocene sediments elevated 1.5 m to 10 m (average 6 m) above the surrounding floodplains. The tract is step-faulted on the west, south and east. As shown in Figure 3.4, a large number of associated faults, with N-S, E-W, NE-SW, and NW-SE trends control the courses of both major and minor streams adjacent to and within the uplifted blocks. Most faults are characterised by vertical movement. Some of these faults correlate with lineations on the Hunting (1981) aeromagnetic map, suggesting that they are basement controlled. Conversely, Monsur (1995) and others consider that the flat surfaces of the Madhupur Tract suggest it is an erosional feature, not tectonically controlled; this alternative view is elaborated in Section 3.5.

The Madhupur Tract is bounded on the west by a series of en echelon faults down thrown on the west, including the Dhamrai, Maijail and Kaliakoir faults. The NW-SW Banar fault (MMP, 1984) along the Banar river defines the northeastern boundary of the Madhupur Tract. On the southeastern side of the Madhupur Tract lies the Meghna floodplain overlooked by the recently uplifted Tippera surface. The Meghna fault zone (Sesoren, 1984), with parallel NE-SW lineations on both sides of the river (Nandy, 1980) is thought to be the surface expression of a deep-seated structure. The Sitalakhya and Arial Khan lineaments parallel the Meghna fault zone. The Meghna floodplain represents a zone of tectonic subsidence between the Madhupur Tract and the Tippera surface. The Dhaka-Tongi block, bounded on all four sides by faults seems to be the most uplifted block.

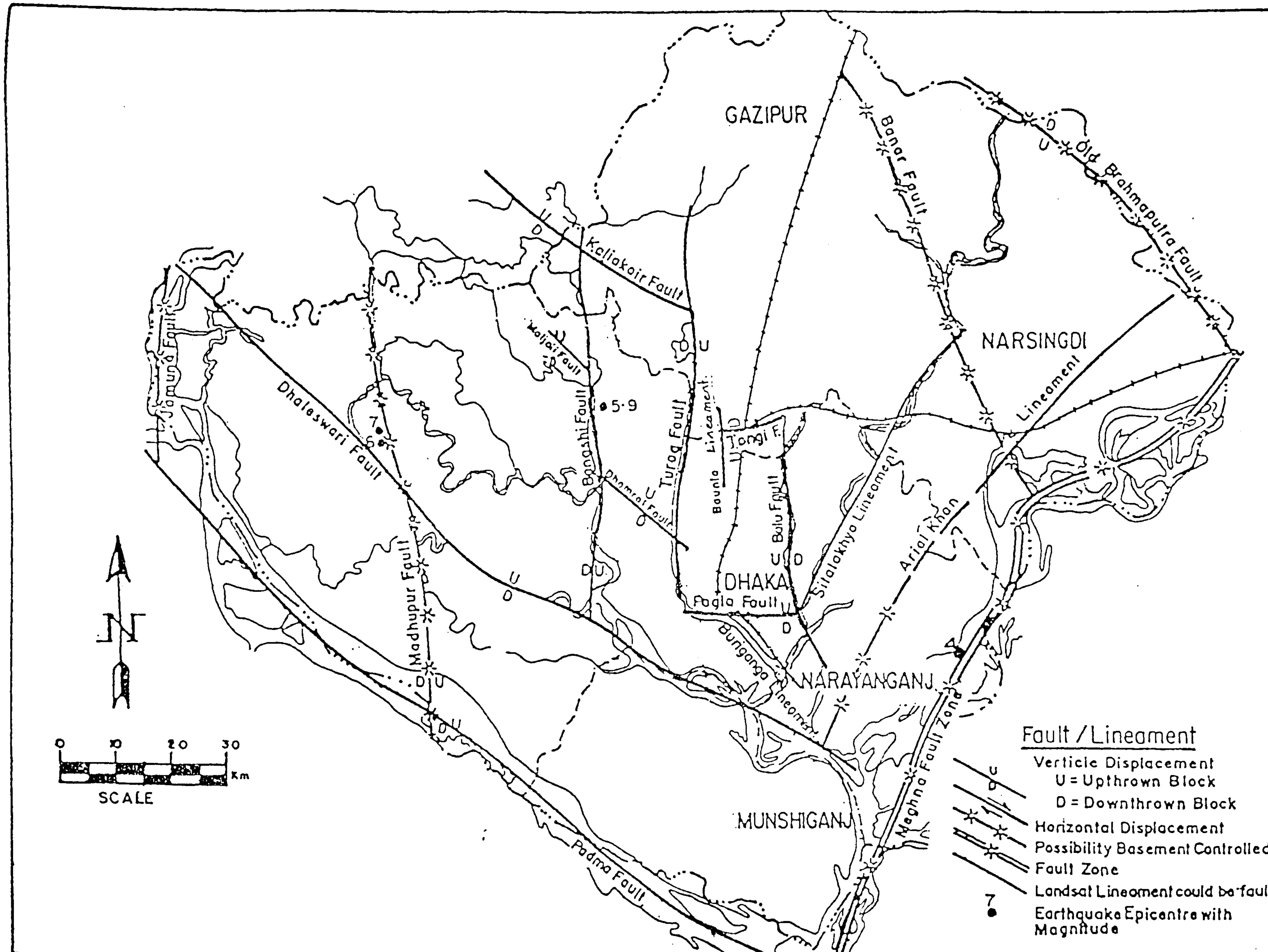


Figure 3.4 Tectonic map of Dhaka region (after EPC/MMP, 1991)

The Madhupur Tract is an easterly-titled fault block. Hirst (1916) first suggested a 'zone of weakness' between the Barind and Madhupur blocks and later Morgan and McIntire (1959) confirmed it. Khandoker (1987) considers that the zone of weakness represents a recently reactivated graben.

3.4 Geology of Greater Dhaka

A geological map of Dhaka city is shown in Figure 3.5. Three cross-sections have been developed from drillers log data available from DWASA (Figures 3.7, 3.8 and 3.9). The borehole locations and lines of geological cross-section are given in Figure 3.6. The cross-sections demonstrate the general features and variations of thickness of different lithologic units. Section A-A' traverses right across Hazaribagh to Shampur. In this section thickness of the clay layer is about 10m. Below the clay the thickness of fine sand varies from 45 to 55 m with occasional clay senses. Section B-B' traverses from Shamoli to Manda. Here the Madhupur Clay is thicker at both the ends of the section and the thickness of the clay varies from 8 to 25 m. Fine sand constitutes a thin layer which pinches-out in the Manda area. The thickness of the Dupi Tila sands varies from 125 to 175 m. The section E-E' runs from Kuratail to Azimpur. The thickness of the Madhupur Clay along these sections varies from 6 to 10 m whereas the thickness of uppermost fine sands of the Dupi Tila Formation varies from 40 to 45 m. The thickness of medium to coarse sand gradually increases and it attains a maximum thickness of 100 m.

At the end of the Pliocene or the early Pleistocene, silty clays belonging to the Dupi Tila Group (or possibly the Girujan clay) were being deposited across the area. The layer is generally not seen in boreholes except in Dhaka city where it is more than 100 m thick. Some coarse sand and gravel near the base highlights the erosional nature of the contact. Variations of grain size are quite small implying a fairly stable environment.

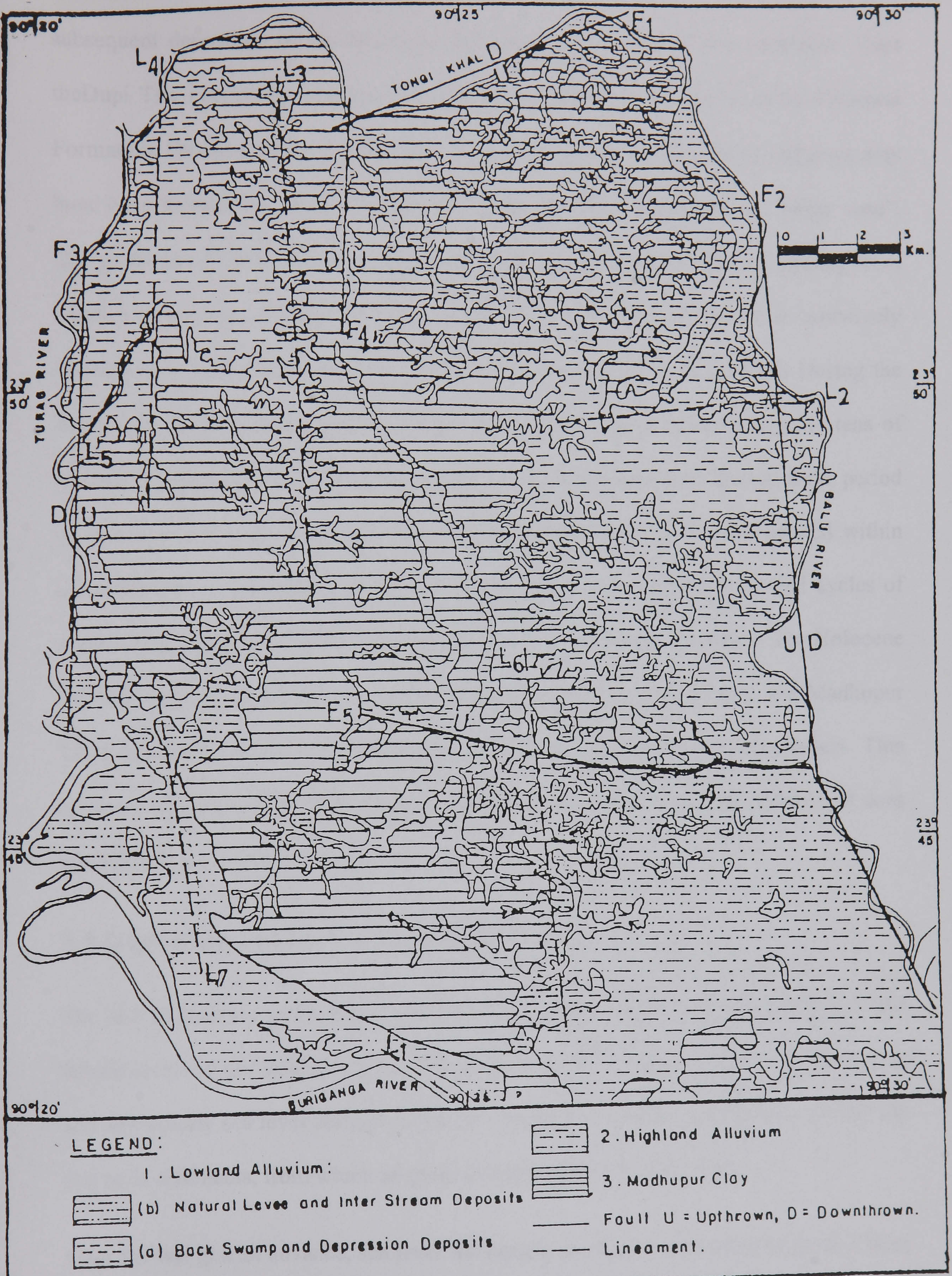


Figure 3.5 Geological map of Dhaka city (after Asaduzzaman and Nasreen, 1990)

Deposition of the Dupi Tila Formation was followed by a period of erosion, and subsequent deposition of the Madhupur Clay Formation. Beyond the Madhupur Tract theDupi Tila Formation is followed by the Lower Alluvial Sequences of the Dhamrai Formation. Davies (1989) considers that the coarsest layers of the alluvial sequence may have been formed from fault-initiated gravity slides in the vicinity of the "hinge zone". The grain size of these deposits indicates a declining energy environment, passing from braided stream to meander belt and finally to a soil horizon which is tentatively correlated with the Madhupur Clay Formation (Madhupur Clay Residuum). During the deposition of the Lower Alluvial Sequence, sea level would have been some tens of meters, to a maximum of a hundred meters, lower than present day. During these period of sea level lows, the Bashabo Formation (Highland Alluvium) was deposited within incised channels previously cut into the Madhupur surface, probably several cycles of erosion and deposition occurred ranging from mid- Pleistocene to modern. The Holocene infilling was not as high as the initial Madhupur surfaces. That is why, the Madhupur Tract apparently seem to be elevated compared to the surrounding floodplain. This apparent elevation of the flat surfaces of the Madhupur is an erosional feature and does not indicate a tectonic event.

3.5 Quaternary History of the Dhaka Region

The late Quaternary geological evolution of the Dhaka region has been critical to the development of the aquifer system. The global climatic changes of the late Pleistocene and particularly sea level changes in the last 30 000 years, have most influenced the top 150 m of sediments, from which all groundwater is drawn (MMI, 1992).

After the last glacial advance, sea level fell rapidly to reach a maximum of about 130 m below its present level 18 000 years ago. The rivers that flowed along the valleys of Madhupur and Barind Tracts would have had sediments transporting capacity much

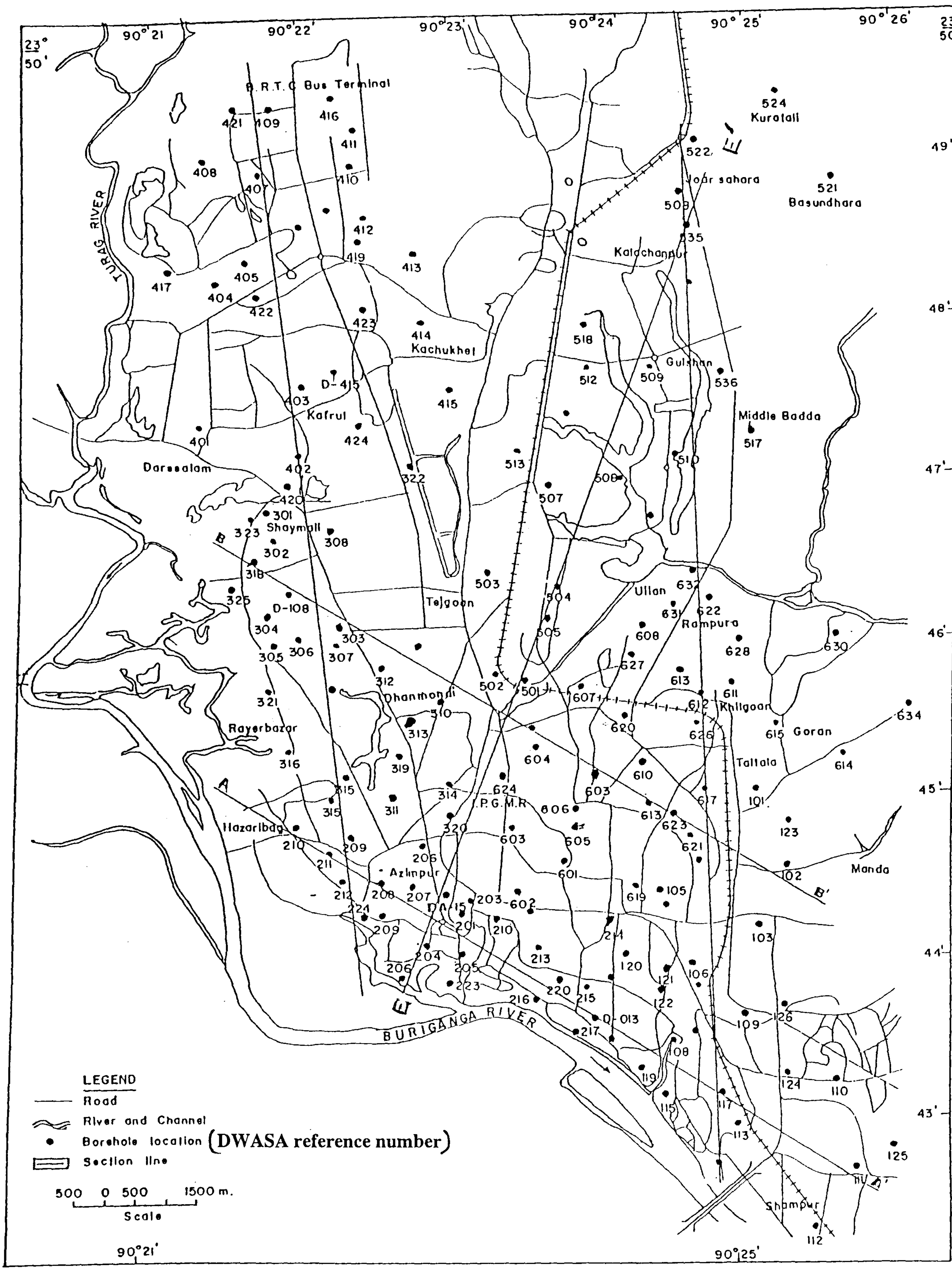


Figure 3.6 Borehole locations and lines of geological cross –sections (after DWASA)

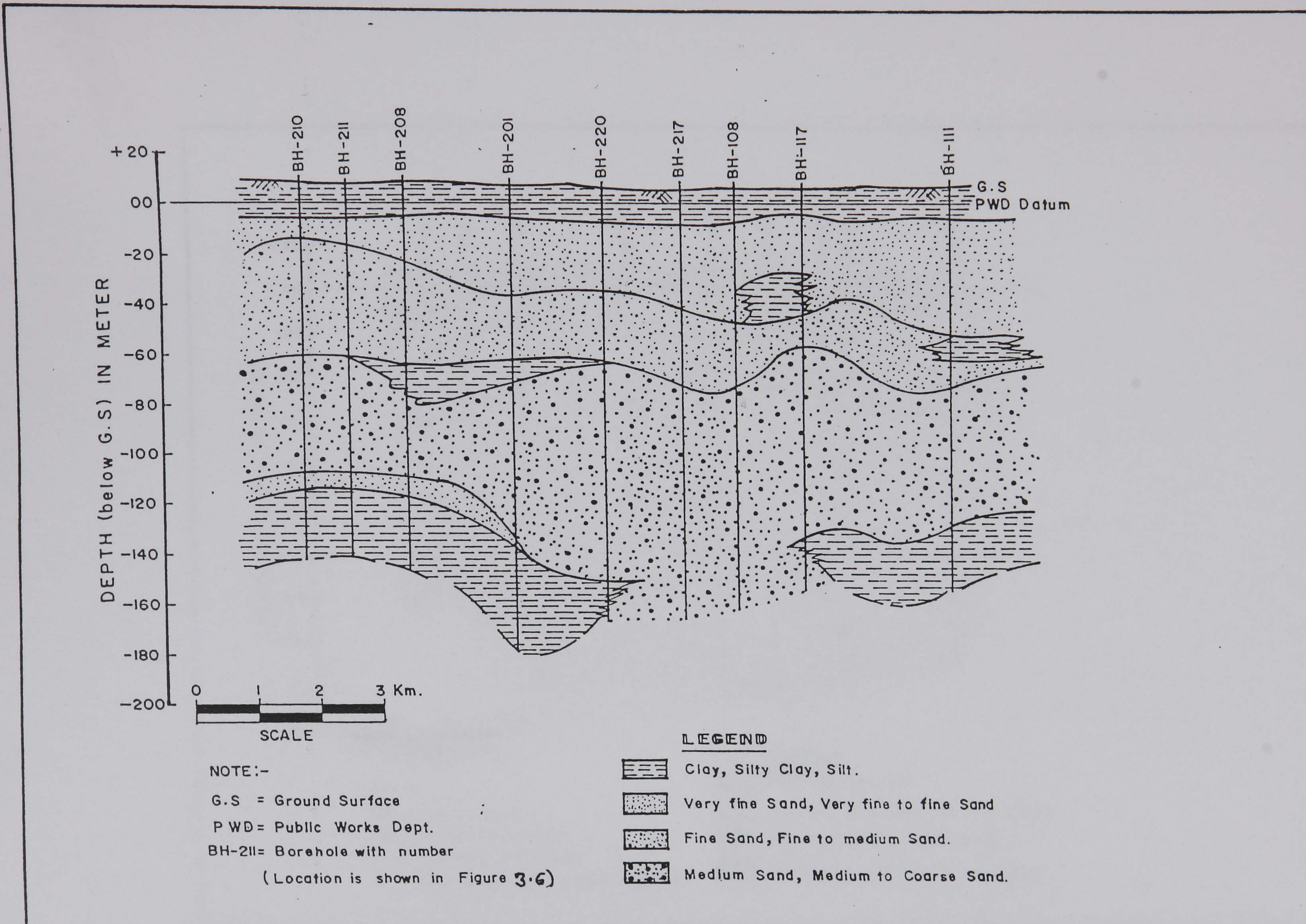


Figure 3.7 *Geological cross-section along A-A' (after Rashid, 1993)*

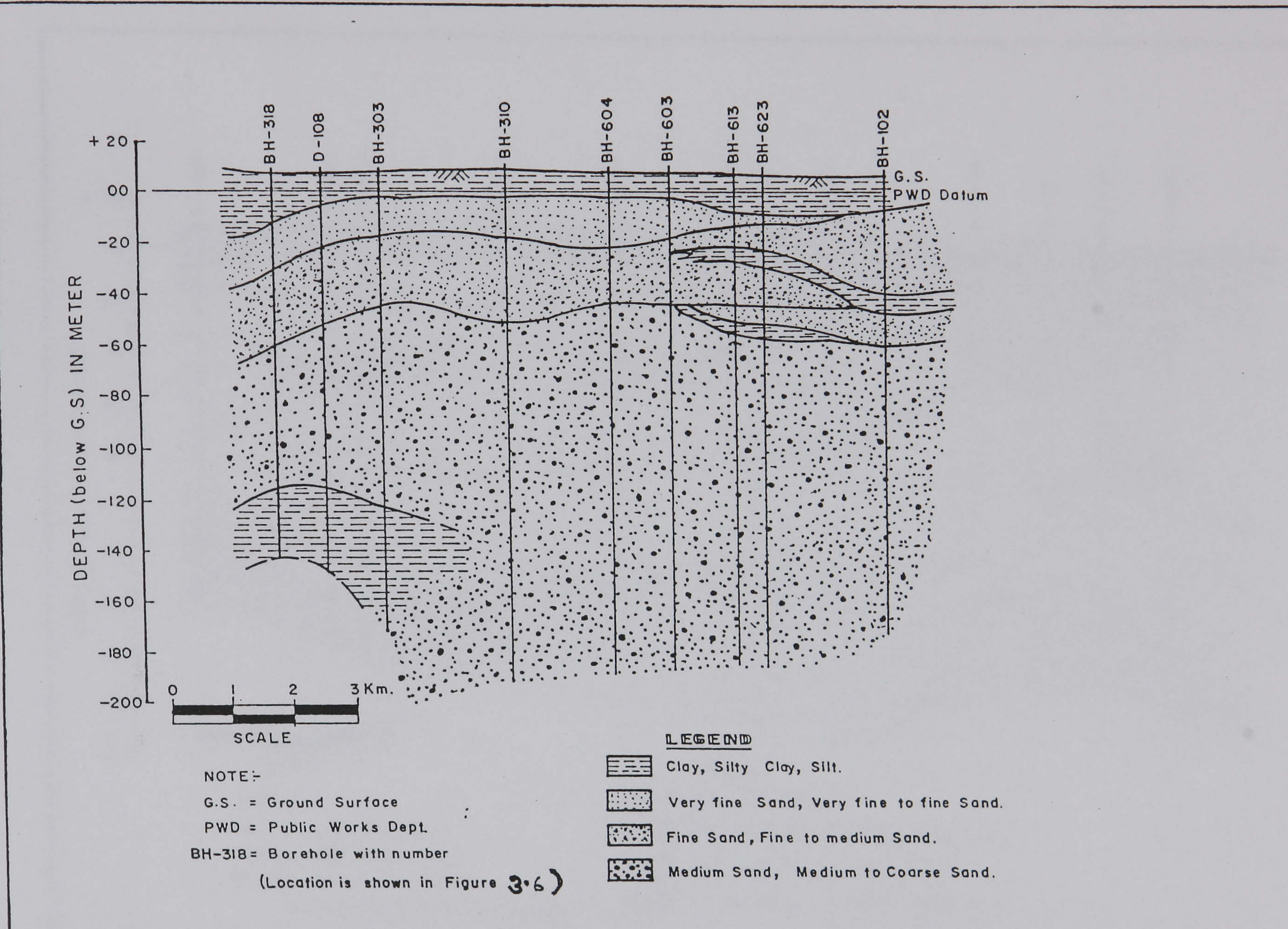


Figure 3.8 Geological cross-section along B-B' (after Rashid, 1993)

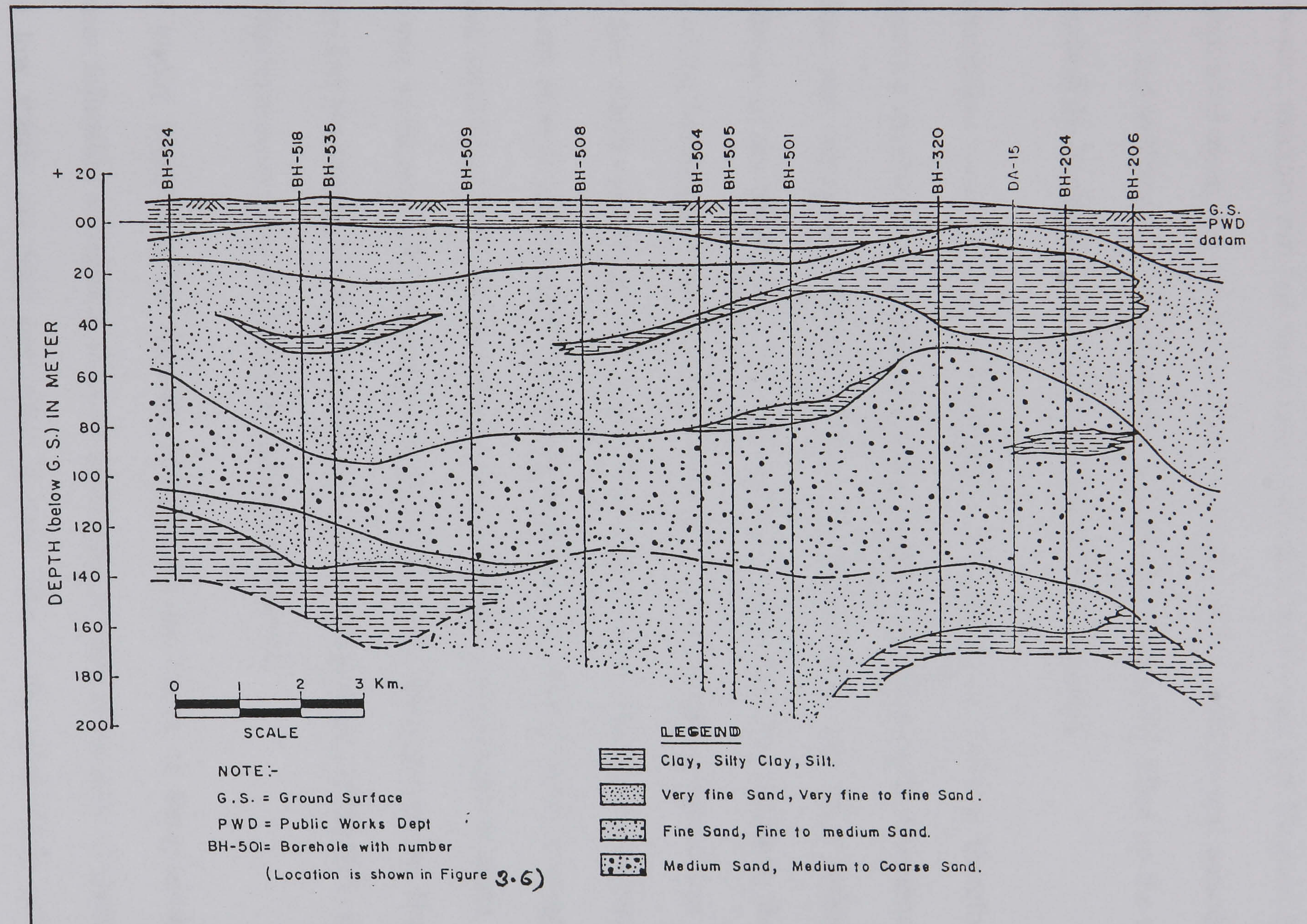


Figure 3.9 *Geological cross-section along E-E' (after Rashid, 1993)*

greater than the present day and carried quite coarse sediments far into the Bay of Bengal.

Sea level rose rapidly after 18 000 years ago to approach its present level by about 8 000 years ago. As the sea level rose, the incised valleys filled up with sediment, first gravel then coarse, medium and fine sands and finally silt. In this way, the Dhamrai Formation was deposited along the course of a proto-Jamuna valley with several periods of river incision and infilling. At the same time, organic clays gradually filled up the tributaries that drained the Madhupur Tract to form the Bashabo Formation.

An alternative view of the development of the Madhupur Tract is therefore that it represents a remnant feature following widespread erosion during the Quaternary glacial maxima and subsequent alluvial infilling. In the extreme, this view holds that the boundaries of the Madhupur Tract are not fault controlled. For example, the western edge of the Madhupur Tract may be truncated by a valley cut during the last major sea level low stand rather than by a fault. This would imply that the maximum depth of Holocene alluvial sediments in the floodplain should be around 120 m, corresponding to the sea level low-stand. Recent studies of the Meghna valley indicate about 120 m of Holocene sediments. The maximum depth of Holocene alluvium in the Brahmaputra Valley and the Meghna Valley are similarly 120 m (Khan *et al.*, 1991). It is most likely that this represents incision during the last glacial interval.

It is highly likely that the remnant Plio-Pleistocene Tracts of Bangladesh, residual features following widespread incision of the land surface at the time of Quaternary sea level low stands, are fault controlled in part. This is the most likely origin of the Madhupur Tract. The hydrogeological implication of this interpretation is that the Dupi

Tila sediments might be present at depth beyond the rivers bounding the Dhaka ctiy region.

3.6 Geological Context of Groundwater Flow

The geological formations and associated hydrogeological characteristics of the study area are shown in Table 3.5.

The depositional pattern of the sediments and other geological features create the context for groundwater occurrence and groundwater flow in the study area. In the floodplain, Holocene to late Pleistocene Dhamrai Formation sediments form a very productive alluvial aquifer system whereas the sands of the Dupi Tila Formation form the main aquifer on the Madhupur Tract, including the Dhaka region. The alluvial silt on top of the Dhamrai Formation acts as an aquitard in the floodplain. On the Madhupur Tract the Dupi Tila aquifer is confined by the Madhupur Clay. Where the Madhupur Clay is absent, the Holocene Bashabo Formation (highland alluvium) or lowland alluvium or floodplain deposits represent the top layer above the Dupi Tila aquifer.

Table 3.5 Hydrostratigraphy of Dhaka region

Age	Stratigraphy	Lithology	Hydrogeological Characters
Floodplain			
Holocene	Floodplain	Alluvial silts, sands & clays	Aquitard
Holocene to Late Pleistocene	Dhamrai Formation[1]	Alluvial sands	Aquifer
Madhupur Tract and Dhaka Region			
Recent	Lowland Alluvium	Swamp, levee & riverbed deposits	-----------
Holocene	Bashabo Formation[2]	Sand (discontinuous)	Connected to surface drainage
Pleistocene	Madhupur Clay Formation	Silty clay with fine sand	Aquitard
		Fluvio-deltaic sand	Aquifer
Plio-Pleistocene	Dupi Tila Formation	Dupi Tila claystone	Aquitard
		Fluvio-deltaic sand	Principal aquifer
Miocene	Girujan Clay	Blue Clay	Base of the aquifer

[1] Davies (1994) and MMI (1992), [2] Monsur (1990)

CHAPTER 4 HYDROGEOLOGY OF DHAKA

4.1 Introduction

Over almost the entire area of Bangladesh, Holocene age fluvio-deltaic sands of the Ganges-Brahmaputra-Meghna river system form a shallow aquifer which exhibits water table conditions. The deeper confined Plio-Pleistocene Dupi Tila aquifer provides strategically important supplies in parts of the country, notably across the Barind Tract in northwest Bangladesh and throughout the Madhupur Tract including the capital city Dhaka. Water level hydrographs in the shallow unconfined alluvial aquifer show a typical pattern of rise and fall with the annual recharge-discharge cycle. However, the situation for the confined Dupi Tila aquifer in Dhaka is completely different. Seasonal fluctuations in water level hydrographs in the city area are small or non-existent. Because the aquifer is so intensively pumped, the groundwater level has been in a more or less steady decline since records began in 1966. The piezometric level of the Dupi Tila aquifer in Dhaka has declined to the extent that the aquifer is unconfined over large parts of the city. Hence the proportion of recharge derived from polluted rivers bounding the city is increasing. Sustainability of the groundwater supply is threatened.

This chapter describes the hydrogeology of Dhaka beginning with a definition of the aquifer system and including a review of the hydraulic properties, the piezometry, groundwater flow, groundwater abstraction and the nature of river-aquifer interaction.

4.2 The Aquifer System

4.2.1 The Dupi Tila Aquifer

The relationship of the aquifer system to the geological stratigraphy has been outlined in Chapter 3. Generalized east-west cross-section of the Dhaka city is given in Figure 4.1. The Dupi Tila Formation constitutes a confined aquifer within the study area, more specifically acting as a multi-layered leaky aquifer system, divided into two units by a discontinuous clay layer (Figure 4.1). Sand units of the Dupi Tila Formation form the main aquifer in Dhaka city, confined by the overlying Madhupur Clay. The combined thickness of the aquifer units varies from 100 to more than 200 m, with an average thickness of about 140 m. The depth of cover over the aquifer from ground surface varies from 8 m to 20 m according to the thickness of the overlying clays. In the conventional aquifer nomenclature of Bangladesh, the Dupi Tila aquifer is termed as a composite aquifer (MPO, 1985 and 1987). Here, it is treated as a single aquifer for convenience of correlation on the basis of grain size, hydraulic properties, and geological occurrence, but in more detail it may be subdivided into 3 sub-units: the Upper Aquifer Sub-unit, the Middle Aquifer Sub-unit and the Lower or Main Aquifer Sub-unit (Salahuddin, 1990).

The Upper Aquifer Sub-unit extends from the base of the Madhupur Clay down to a depth of 16 to 60 m from ground surface; its thickness is up to 50 m with an average value of about 20 m. It is composed of very fine to fine sand.

The Middle Aquifer Sub-unit is composed of fine to medium sand and contains clay lenses which are thick but apparently discontinuous, being absent in places. The depth of this unit varies from 50 to 115 m from the ground surface and the thickness ranges between 15 and 80 m with an average value of about 50 m.

The Lower or Main Aquifer Sub-unit is mainly composed of medium to coarse sands with some gravel at depth. The depth of the aquifer varies from 115 to 200 m from the ground surface where the thickness ranges from 15m to more than 125 with an average value of about 70 m. The thickness is at a maximum in the central part of the city and a minimum in the north of the city.

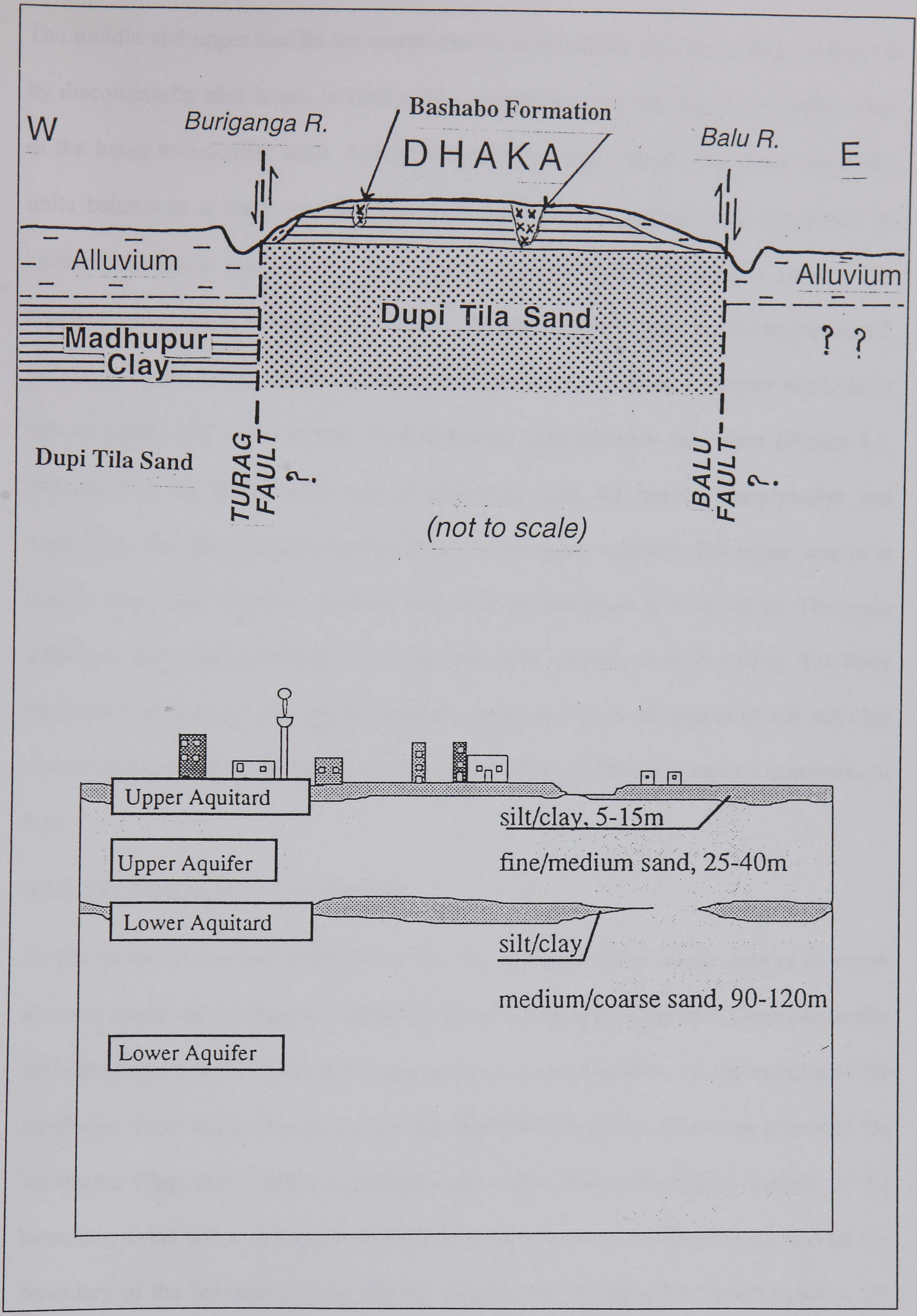


***Figure 4.1** Generalized geological cross-section of the Dhaka aquifer system, East West (top), with detail of Dupi Tila aquifer system (bottom)*

The middle and upper aquifer are continuous in some places, but are partially separated by discontinuous clay lenses in others. Discontinuous clay lenses are found within each of the lower two-aquifer units. Available aquifer test data indicate that these three sub-units behave as a single aquifer system in which all are hydraulically connected by vertical leakage to some extent. They form a multi-layered leaky aquifer system. The tripartite subdivision of previous workers mentioned above may be overcomplicated. Based on borehole logs and the experience of previous modelling a simpler subdivision into an upper and lower aquifer divided by the discontinuous clay layer (Figure 4.1, bottom) may be more useful and is ultimately used for further interpretation and modelling. The upper aquifer is situated below the upper aquitard. The upper aquifer is mainly composed of fine to medium fine sand the thickness is 25 to 40 m. The main aquifer is composed of medium to coarse sand with a thickness of 90-120 m. The layer separating the lower, main aquifer from the upper aquifer is composed of silt and clay and is not present throughout the whole region, varying a thickness up to a maximum of 8 m.

4.2.2 The Madhupur Clay Aquitard

At the surface across the uplifted Tract is the Madhupur Clay, which acts as an upper aquitard confining the Dupi Tila aquifer below. This layer is composed of low permeable silts and clays. It is 6 to 10 m and in some places up to 15 m thick. At the margins of the Madhupur Tract discontinuous sands of the Bashabo Formation, which can penetrate the Madhupur Clay, may contain a shallow water table. Recent floodplain deposits of the bounding rivers act as the upper aquitard in some places. In the floodplains beyond the boundary of the Madhupur Tract alluvial sands of the Dhamrai Formation underlie the active floodplain (incorporated as "Alluvium" in Figure 4.1 and act as an unconfined aquifer.

4.2.3 Base of the aquifer system and the 'deep aquifer hypothesis'

The base of the aquifer system is composed of a widespread thick clay layer presumed to represent the Girujan Clay Formation, which forms an effective hydraulic basement to the aquifer. In recent years, there has been much discussion about the possibility of exploiting 'deep aquifers' beneath Dhaka city following proposal of the 'deep aquifer hypothesis' by Jones (1985). The hypothesis is based on lithological and electric logging data from deep boreholes showing sand and sandstone horizons within the upper 2 km of sediments below the clay which underlies the Dupi Tila Formation. There has however been some confusion about what is meant by 'deep' aquifers. Based on BWDB deep exploratory boreholes (Figure 4.2) there is no evidence of any significant aquifers below those already being exploited in Dhaka, within the depth range of conventional water well technology. However, Jones has suggested investigating what should perhaps be called a "very deep" aquifer at a depth of more than 1 km, where it is presumed that the likelihood of encountering deltaic sands of sufficient permeability is high. The groundwater quality of this "very deep" aquifer, if the aquifer exists, remains to be defined but it may be unsuitable for use as a drinking water resource.

4.3 Hydraulic Properties

Hydraulic properties of the Dupi Tila aquifer have been obtained from various published aquifer tests, laboratory permeability tests, grain size analyses and in some areas from the relationship between river stages and adjacent groundwater levels. A summary is provided below.

Integrated results of aquifer tests have been reported by Parsons (1980), BWDB (1984) and the BGS (Barker *et al.*, 1989). The Parsons and BWDB results are cited in Table 4.1. A variety of methods of analysis were used including application of aquifer type curve methods, but the original data are not available for review. The BGS tests were

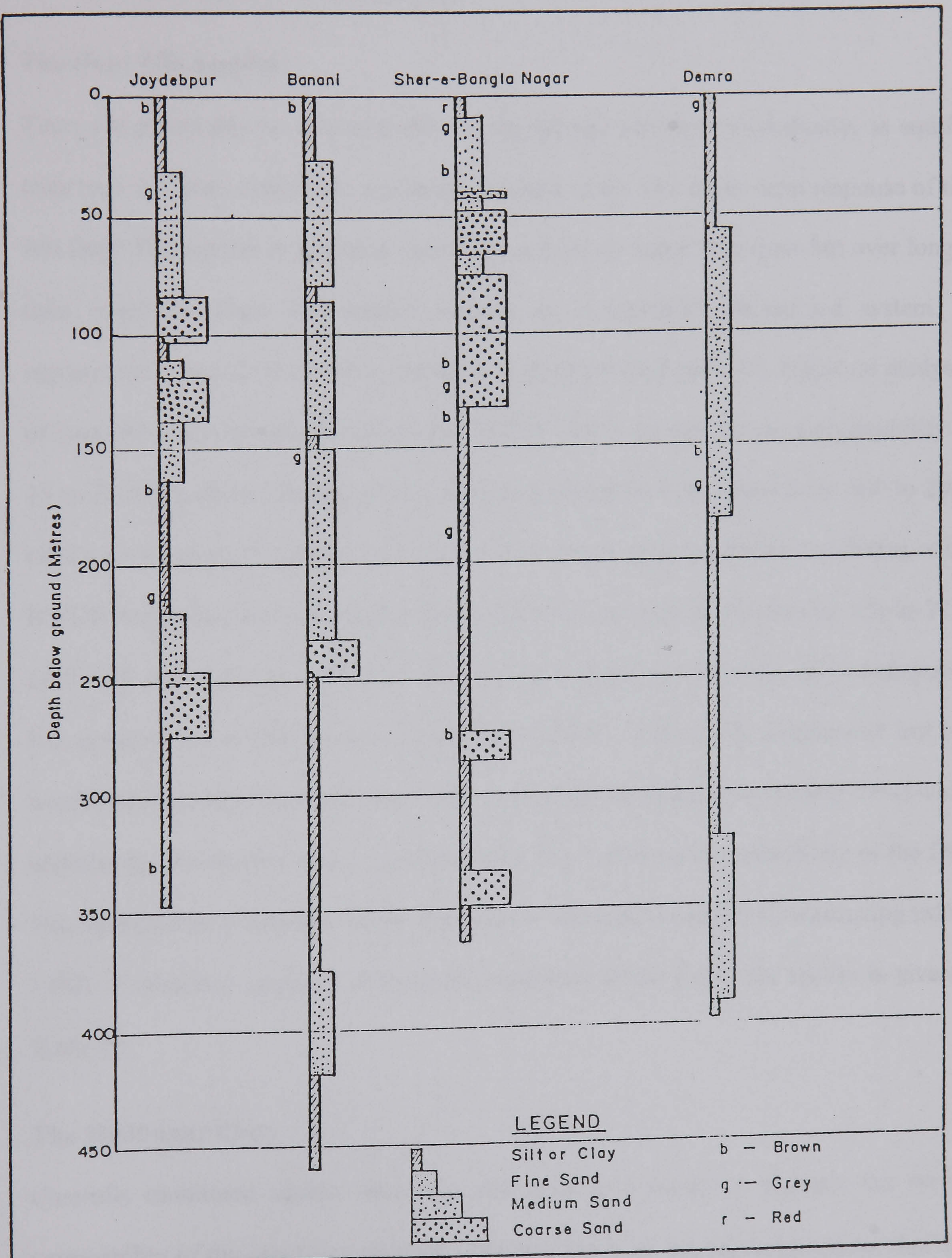


Figure 4.2 BWDB deep exploratory boreholes near Dhaka

ultimately analysed by application of finite element modelling (Barker *et al.*, 1989), which yielded vertical and horizontal permeabilities, and the confined and unconfined storage coefficients for both aquifers and aquitards. The results are considered next.

4.3.1 Permeability and Transmissivity

The Dupi Tila Aquifer:

There are practically no data available for the aquifer sub-units individually, as aquifer tests have not been carried out separately for these units. The short- term response of the full Dupi Tila aquifer to pumping indicates confined or leaky behaviour but over longer time spans the Dupi Tila aquifer behaves as a regionally unconfined system. A representative aquifer response to pumping is illustrated in Figure 4.3. Based on analyses of constant discharge pumping tests (EPC/MMP, 1991) the aquifer has a permeability of 15 to 30 m/d with an average of 20 m/d, and the transmissivity varies from 500 to 2000 m^2/d with an average value of 1600 m^2/d. These ranges corresponds well with that of the BWDB which has derived transmissivity values for the aquifer of between 620 to 2235 m^2/d with an average of 1850 m^2/d. The high transmissivity of the aquifer is undisputed. It is however lower than the more transmissive (3000 - 5000 m^2/d), unindurated and less weathered, Late Pleistocene alluvial sands of the Dhamrai Formation (Davies, 1994) which underlie the floodplains west of the Madhupur Tract. The lower permeability of the Dupi Tila sands has been attributed to the formation of secondary minerals by weathering (MMI, 1992). A tabulated summary of hydraulic properties of the Dupi Tila aquifer is given in Table 4.1.

The Madhupur Clay:

Carefully monitored aquifer tests may also provide a means to estimate the vertical permeability of the overlying aquitard, although this is an aggregate parameter that does not explicitly recognise the effects of layering. The following results (Table 4.2) have

Table 4.1 Summary of hydraulic properties of the Dupi Tila aquifer, Dhaka

Location in Dhaka	**Transmissivity (m^2/day)**	**Storage coefficient**	**Source**
Abul Hasnat Rd	1501		Parsons (1980)
Azimpur	1048		Parsons (1980)
Azimpur	2689	$4.7 * 10^{-4}$	Parsons (1980)
Dhanmondi	1809		BWDB (1979)
Dhanmondi	794		Parsons (1980)
Fakirapul	880		Parsons (1980)
Farashganj	1699		Parsons (1980)
Faridabad	1366		Parsons (1980)
Fulbaria	1005		Parsons (1980)
Gandaria	1105		Parsons (1980)
Kawran Bazar	1828		Parsons (1980)
Khilgaon	901		Parsons (1980)
Khilgaon	1429		Parsons (1980)
Lalmatia	3092		Parsons (1980)
Lichu Bagan	944		Parsons (1980)
Mahakhali	1459		Parsons (1980
Banani	1500		Parsons (1980)
Mirpur	422	$3.5 * 10^{-4}$	BWDB (1979)
Rayer Bazar	1407		Parsons (1980)
Tejgaon	1184		Parsons (1980)
Uttara	1001	$9 * 10^{-4}$	BWDB (1979)
Dhamrai	1628	$3.0 * 10^{-4}$	BGS (1989)
Gymkhana	435	$16 * 10^{-4}$	Welsh (1977)
Tabulated Average	1353	$8.3 * 10^{-4}$	

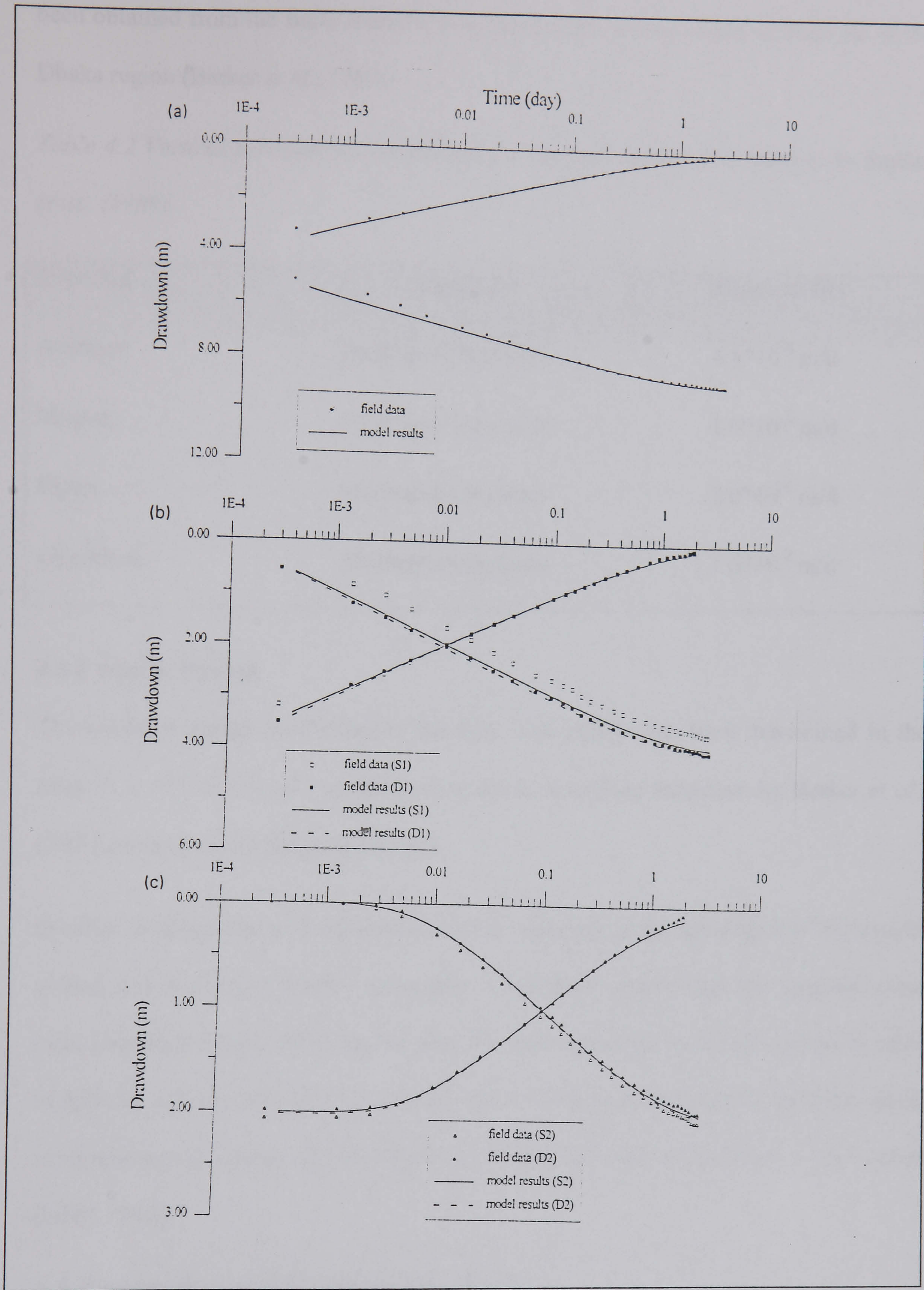


Figure 4.3 *Typical aquifer response to pumping (comparison between field and modelled) from Dhaka, (a) pumped well, (b) observation well, 10m from pumped well and (c) observation well, 100m from pumped well (after Mia and Rushton, 1997)*

been obtained from the finite element analytical solutions for the tests carried out in the Dhaka region (Barker *et al.*, 1989).

Table 4.2 Vertical permeability of Madhupur Clay from aquifer test analysis by Barker et al., (1989).

Location	**Aquitard**	**Permeability**
Azimpur	Madhupur Clay/sand	$6.5*10^{-4}$ m/d
Mirpur	Madhupur Clay/sand	$1.6*10^{-3}$ m/d
Uttara	Madhupur Clay/sand	$2.2*10^{-4}$ m/d
Gymkhana	Madhupur Clay/sand	$1.6*10^{-2}$ m/d

4.3.2 Aquifer Storage

The confined storage coefficient of the Dupi Tila aquifer has been determined in the range 7×10^{-6} to 5×10^{-5} by the finite element modelling technique by Barker *et al.*, (1989) on the basis of pumping test data.

Specific yield appears to be determined by the lithology of the upper part of the aquifer system and is strongly depth – dependent. Correlation of lithology and regional water table responses (MMI, 1992) for the Dupi Tila Formation has indicated a range in value of specific yield from 0.005 for clays, to 0.08 for fine sands and 0.30 for medium sands, in comparison to a range of 0.03 for silt to 0.16 for fine sands of the Dhamrai Formation (MMI, 1992).

4.4 Piezometry and Groundwater Flow

Throughout the Madhupur Tract the natural condition is for the level of saturation in the Madhupur Clay to be close to the ground surface. The shallow water table in the Madhupur Clay is typically at 2 – 5 m depth. The Madhupur Clay Formation confines the Dupi Tila aquifer but the piezometric surface of the aquifer is below the Madhupur Clay water table, indicating a vertical hydraulic gradient downwards across the aquitard. This implies that recharge to the Dupi Tila aquifer is by topographically-driven vertical leakage through the Madhupur Clay. In the Dupi Tila sands, the natural system is that groundwater flows towards the boundary of the Madhupur Tract. Here, the aquifer is likely to be in hydraulic contact with the shallow alluvial sands of the Dhamrai Formation, which overlies the Dupi Tila in the floodplain areas. In some places the Dupi Tila sands are exposed along sections of the surrounding riverbeds. It is these regions of lower elevation which would be expected to be groundwater discharge zones under natural conditions. These are the conditions which are observed at an equivalent occurrence of the Dupi Tila aquifer, in northwest Bangladesh on the Barind Tract (Ahmed and Burgess, 1995). On the Barind Tract, groundwater is used for dry-season irrigation and the aquifer is in a less advanced state of development than in Dhaka on the Madhupur Tract (Hasan *et al.*, 1998).

The regional pattern of groundwater flow at the southern end of the Madhupur Tract has been much disturbed by intensive abstraction at Dhaka. The piezometry of the Dupi Tila aquifer for the end of the dry season in 1997 is illustrated in Figure 4.4. Large-scale abstraction has resulted in an extensive cone of depression centred on the city. The aquifer has become unconfined over large parts of the city. Drawdown in the aquifer continues to increase at a rate of approximately 1.0 m per year as indicated by monitoring piezometers (Figure 4.5). Over the past 30 years the cone of depression in the aquifer has developed to the stage that it now extends to the major river courses that delineate the southern portion of the Madhupur Tract (Figure 4.6). The steep piezometric gradients close to the River Buriganga suggest that the further spread of the cone of depression is prevented by leakage induced from that river. To the east of the city,

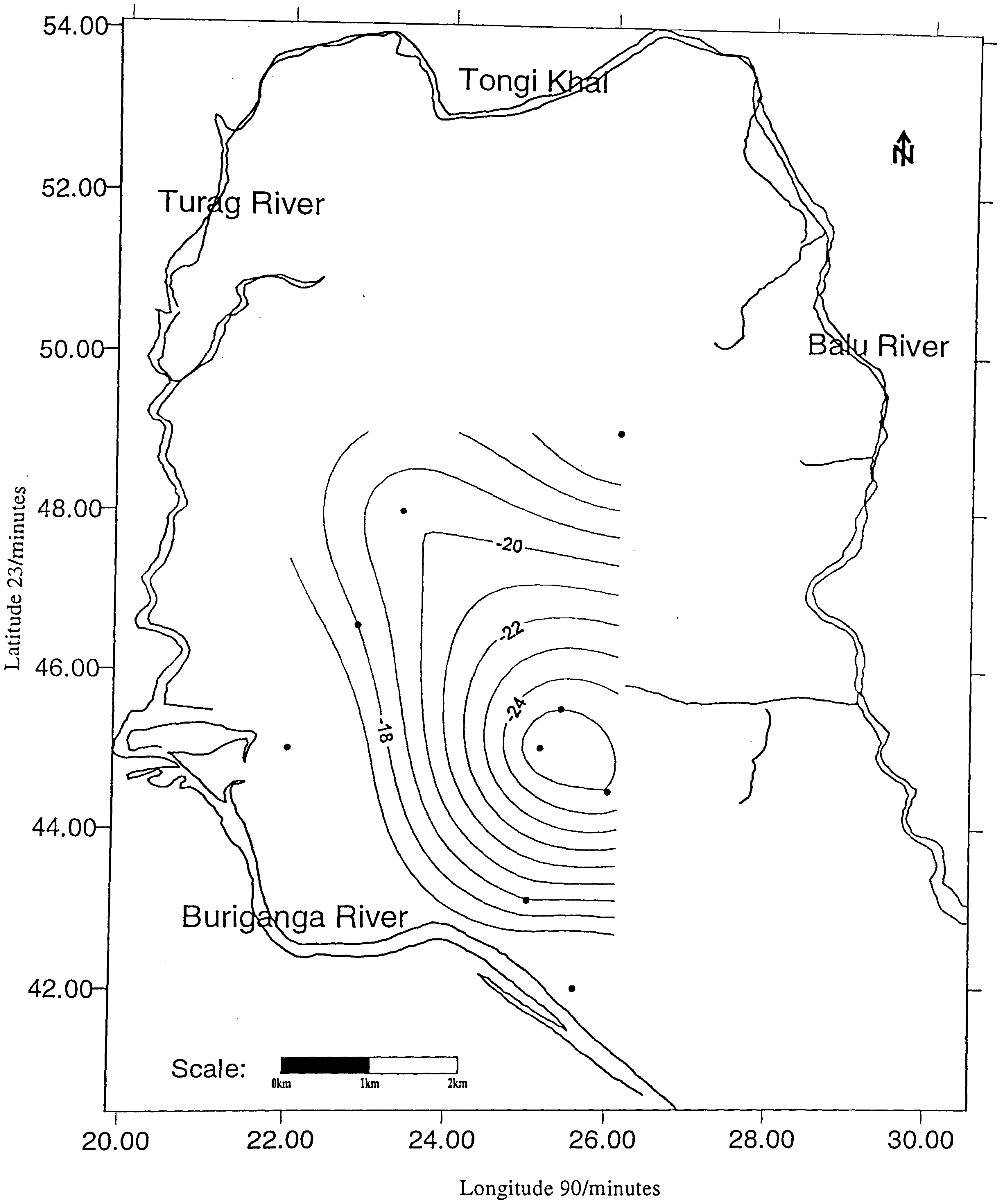


Figure 4.4 Piezometry (contour in metres) of the Dupi Tila aquifer for the year 1997 (data from BWDB)

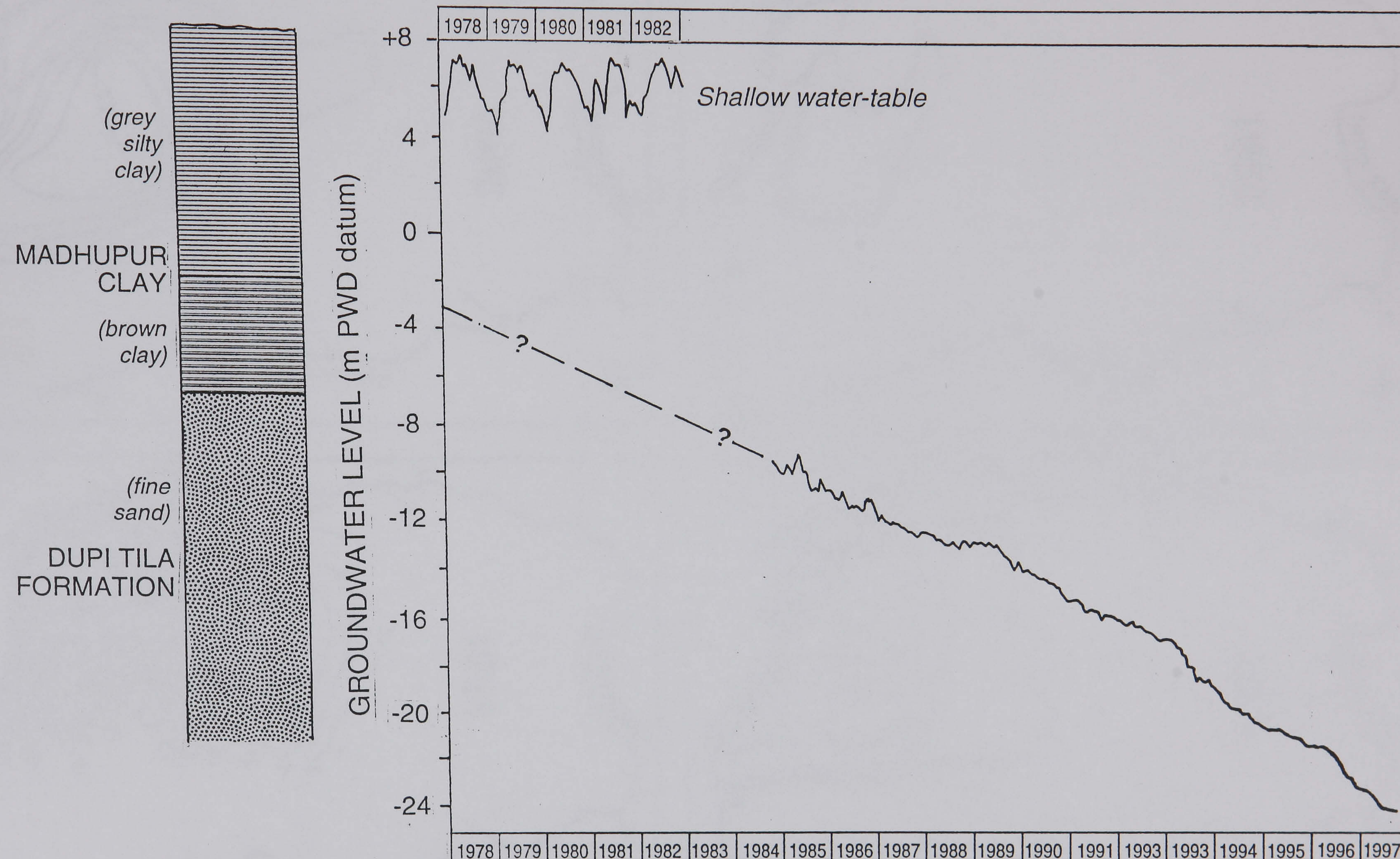


Figure 4.5 *Long-term hydrograph of a monitoring borehole, central Dhaka (data from BWDB)*

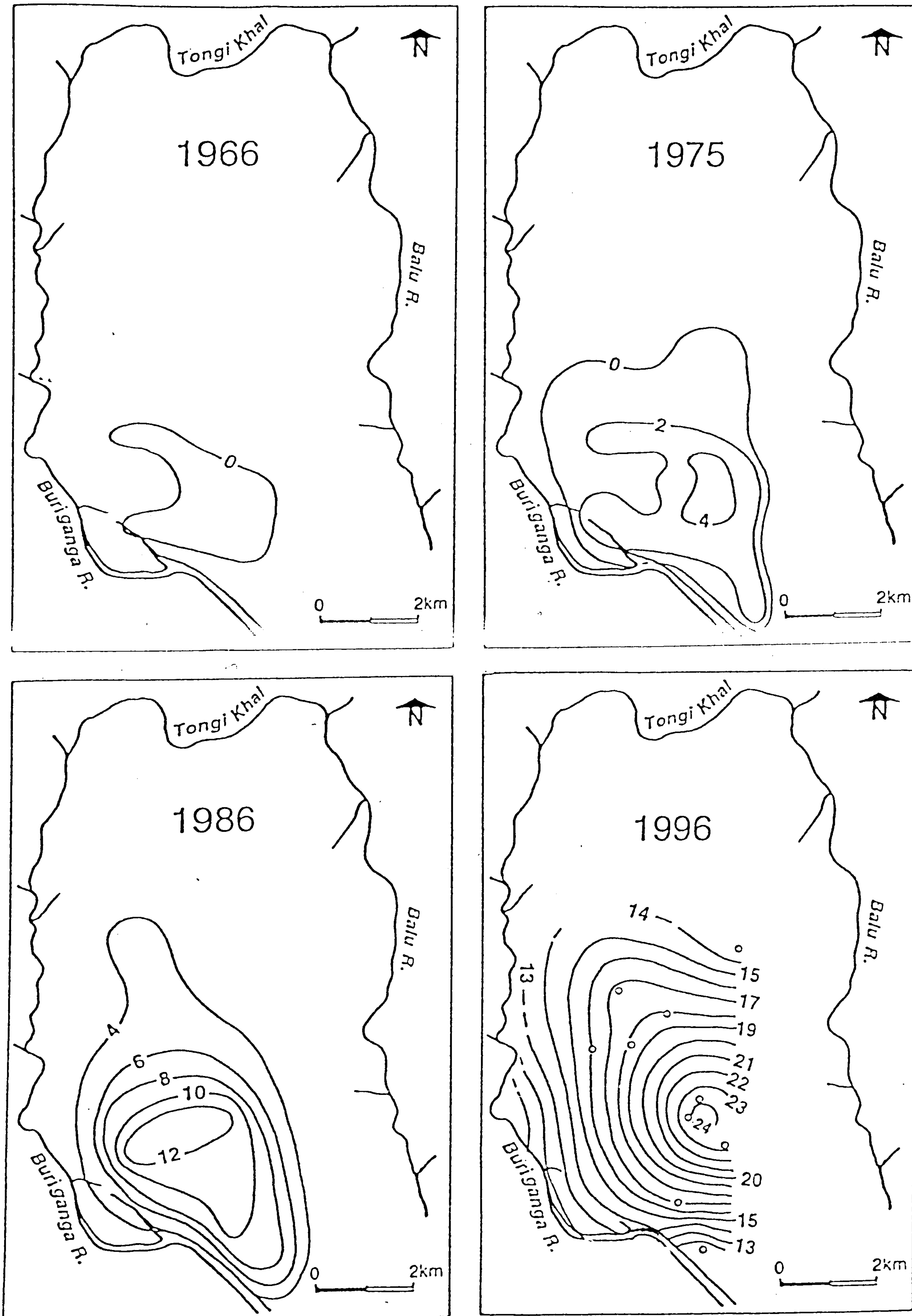


Figure 4.6 *Sequential piezometry of the Dupi Tila aquifer, 1966-1996 (as water level below PWD datum, in meters) (data from BWDB).*

expansion of the cone of depression is reduced by recharge induced from the low – lying deeply – flooded land between Dhaka and the River Balu. It is apparent that the impact on the aquifer of pumping within Dhaka is restricted in a regional sense by induced recharge. The more recent expansion of the cone of depression northwards is the effect of new abstraction boreholes drilled as Dhaka has grown in this direction.

There is uncertainty regarding the amount and mechanism of vertical recharge through the Madhupur Clay with such a low permeability. However, it is generally believed that there can be considerable leakage through the clay if there is a sufficient head gradient between the shallow water table and piezometric surface of the aquifer. There is also uncertainity about the scale of induced recharge that is possible from the bounding rivers, given that any of the details of the river/aquifer contacts are unknown. The relative significance of these two recharge sources is the subject of modelling investigations in Chapter 7. Implications for the evolution of groundwater quality are discussed in Chapter 5.

4.5 Groundwater Abstraction and Use

Throughout Dhaka, groundwater is abstracted from the Dupi Tila aquifer by the Dhaka WASA and a number of private organisations. The DWASA abstracts the largest volume of water with nearly 220 tubewells operating in 1998. More than 95% of the total distribution supply is taken from groundwater. Surface water from the Buriganga River at Chadnighat amounts to less than 5% of the total. Increase in total abstraction and in the number of DTWs since 1980 are shown in Table 4.3. The population increase and groundwater abstraction is illustrated in Figure 2.6.

Table 4.3 Groundwater abstraction by DWASA and population increase in the city

Year	No. of DTWs	Groundwater Abstraction (MCM) from the Dupi Tila aquifer	(%) of water distributed by DWASA	Population (m)
1980	80	106.27	94.85	3.0
1985	115	139.52	95.85	4.0
1990	136	177.23	96.77	6.0
1998	220	270.00	95.66	10.0

The abstractions from private wells are not known properly. DWASA (EPC/MMP, 1991), estimated total abstraction by private organisations to be not less than 41 MCM pa, from 200 boreholes concentrated mainly in the two industrial areas of the city, Hazaribagh and Tejgaon, i.e. about 23% of the DWASA 1990 abstraction. The data, despite the best available, are considered inaccurate, however.

In Dhaka, public water supply falls short of demands although the groundwater abstraction rate has already exceeded the recharge as evidenced by the falling piezometric levels. In 1998, the supply was only about 50% of the water demand for about 10.0 million people at a usage rate of 0.15 m^3/day/capita. Groundwater abstraction continues to increase.

4.6 River-Aquifer Interactions

The major rivers

Groundwater systems throughout Bangladesh are intimately interlinked to the intricate network of river channels (Wardlaw and Moore, 1996). The relationship of this vast network of rivers to the shallow aquifer systems across the country has not been an issue for the large tracts of rural Bangladesh as it has now become for Dhaka city, although, a recent modelling study (Nobi and Gupta, 1996) has indicated the significance of stream – aquifer interaction in the southwest coastal region of Bangladesh. The likelihood of river influence on groundwater levels in Dhaka has long been recognized (Welsh, 1977; Solomon and Chidley, 1980) but never well – defined quantitatively. The critical issue governing induced recharge is accepted to be the degree of penetration of the aquifer, yet this is unknown in detail. Welsh (1977), by analysing the attenuation of river stage fluctuations in adjacent aquifers, provides a useful indication of the continuity between the Dupi Tila aquifer and the rivers in Dhaka. Water levels in the Buriganga were shown by Welsh to vary annually from a low of about 1.2m to a high of about 8.7m PWD for the period from 1966 to 1977. The variation of river levels during 1988/1989 is shown in the following Table (Table 4.4).

The significance of the connections between rivers and aquifers generally becomes more apparent only when large-scale groundwater abstraction near a river takes place. To analyse the degree of connection it is essential that the piezometric levels in the aquifer are observed at both sides of the river. The hydraulic connection of the river Buriganga with the aquifer underlying Dhaka can not be adequately assessed without a knowledge of the piezometric condition on the opposite side of the river (Hasan *et. al.*, 1998a).

Nevertheless, as an indication, comparison between the river base levels and the base of the upper aquitard is shown in Table 4.5. These data highlight the potential for direct contact between the river and the aquifer and for facilitated induced recharge in the vicinity of the Bangladesh-China Friendship bridge site and the Babu Bazar-Zinzira Second Buriganga bridge site. Typical geological cross-sections through the river Buriganga and possible modes of river-aquifer interaction are shown in Figure 4.7. The Figure shows that much of the riverbed is sandy and two recharge paths are apparent.

Table 4.4 Variation of river water levels during 1988-1989 (data from BWDB).

Name of the River	**Stage (m above PWD)**	
	Minimum	Maximum
Buriganga	1.3	8.1
Turag	1.0	6.8
Balu	1.8	5.1
Tongi	1.2	4.8
Dhaleswari	3.5	8.3

Water may infiltrate readily into the sandy riverbed, and then flow laterally into the brown sand layer, thus providing a much larger area for leakage through the Madhupur Clay into the main aquifer. The second pathway occurs from the Dhamrai Formation sands in Keranaiganj through the gap in the Madhupur Clay and thence by lateral flow in the main aquifer.

Piezometric data available from the Bangladesh Water Development Board (BWDB) confirm that the rivers are in hydraulic continuity with the aquifer system (Khan, 1989). Water levels in the upper aquifer rise steeply towards the river Buriganga, and water levels in boreholes within 2 km of the rivers fluctuate with river stage (Bhuiyan, 1995).

Interaction between other surface water and groundwater

Surface water bodies within Dhaka city includes natural lakes (the Gulshan, Dhanmondi and Banani lakes), artificial ponds and channels. Particularly where they are perennial these must contribute some recharge throughout the year, although at present there is some doubt about their contribution and development is leading to their filling.

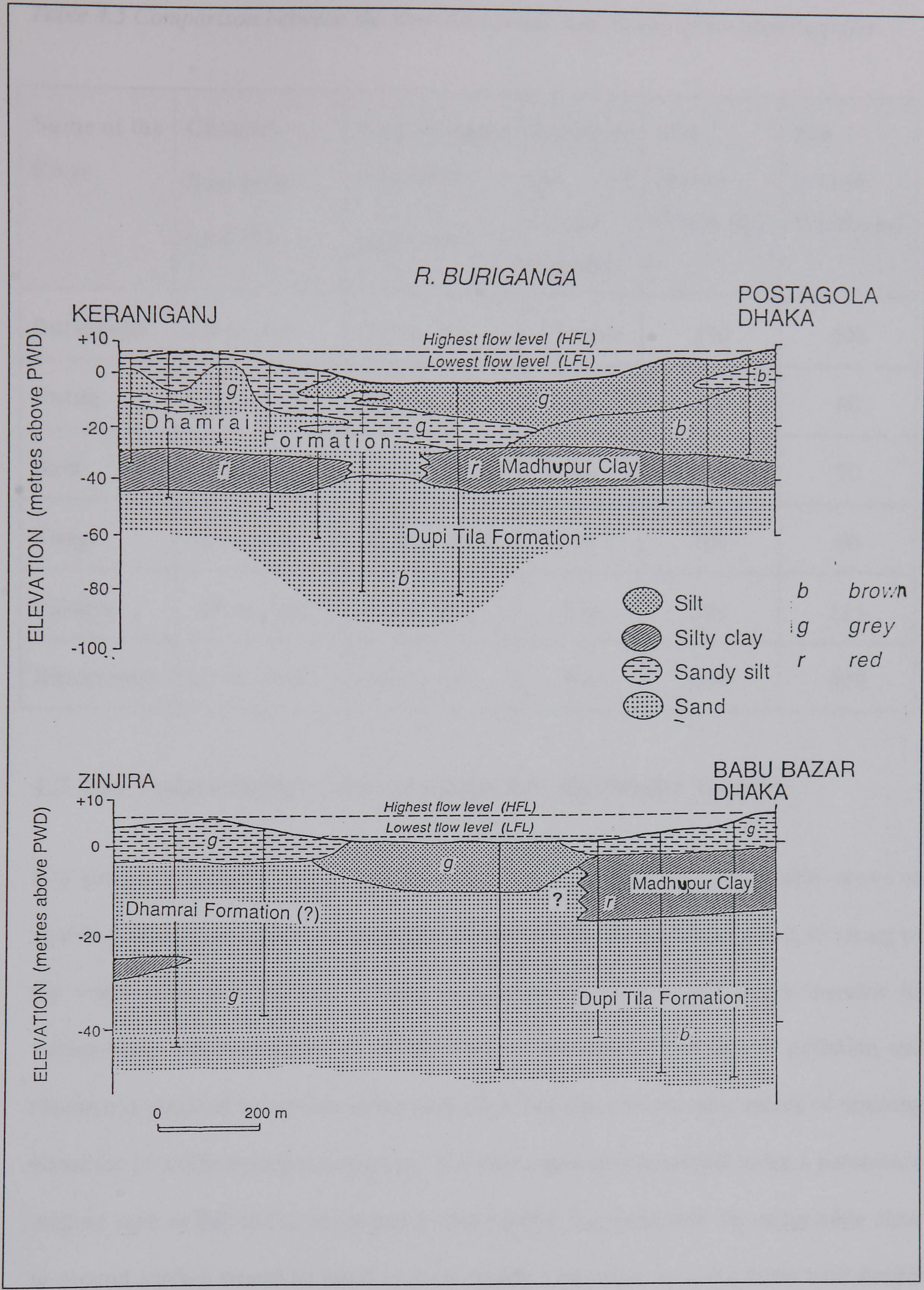


Figure 4.7 Typical geological cross-section along the river Buriganga, Bangladesh China Friendship Bridge site (top), Babu Bazar-Zinzira second Buriganga bridge site (bottom)

Table 4.5 Comparison between the river base levels and the top of the upper aquifer.

Name of the River	Channel Base level (m PWD)	Base of upper Aquitard (m PWD)	Penetration of Upper Aquifer	Wet Season Width (m)	Dry Season Width (m)
Buriganga	2.8 to –6.0	-2.0 to –5.5	Variable	330	200
Turag	0.6 to –10.0	-12.3 to –22.5	No	170	80
Balu	0.5 to –3.5	-5.5 to –12.0	No	100	70
Tongi	0.5 to –2.5	-22.0 to –32.0	No	100	60
Lakhya	-5.9 to –10.7	-2.0 to –26.5	Yes	200	125
Dhaleswari	2.5 to –10.5	-0.0 to –2.5	Yes	600	400

4.7 The Vulnerability Concept Applied to the Dhaka Aquifer

It is generally accepted that the presence of a clay layer with low permeability above an aquifer protects the aquifer to pollution. However, intensive pumping and lowering of the water table can enhance vertical leakage to the aquifer and hence increase its vulnerability. An assessment of vulnerability of this aquifer in terms of pollution and resource is required to provide better protection because it is the only source of drinking water for 10 million people in the city. If a quick general assessment using a parametric method such as DRASTIC is applied to this aquifer, the areas with the water table close to ground surface would be rated as more highly vulnerable than the areas with deeper water table (such as central part). As the aquifer in Dhaka city is deep so the movement of water from the land surface through the vadoze zone is slow and it may take many years after a chemical first enters the ground before it affects the quality of groundwater supplies. The high transmissivity of the aquifer may counterbalance the effect of intensive withdrawal by allowing groundwater from a larger area to contribute to the withdrawal. A good hydraulic contact between the Buriganga River and the aquifer may be regarded as a defense mechanism reducing the resource vulnerability of the aquifer. However this contact could increase the vulnerability to pollution of the aquifer as the river Buriganga itself is polluted by industrial wastes. The abstraction boreholes close to the river are more vulnerable than the boreholes situated far away from the river.

Based on the natural characteristics of the strata separating it from the land surface the aquifer pollution vulnerability is not very high. Although the vulnerability would be high at places such as Tejgaon and Hazaribagh where contaminant loads from chemical and tanning industries could come into contact with the aquifer. The types of pollutant and the degree of pollutant attenuation which is currently unknown for Madhupur Clay will ultimately determine the vulnerability of the Dhaka aquifer. Additionally, contaminants may in some places by pass Madhupur clay and, therefore, there is no geological based protection of the aquifer in these areas. The mechanism and rate of vertical leakage through the Madhupur Clay may provide the key to determine the vulnerability of the aquifer. In conclusion, it can be said that the Dupi Tila aquifer in Dhaka is vulnerable to pollution even if the hydraulic situation can be stabilised in future.

The simple parametric vulnerability assessment methodology DRASTIC has been applied to the Dupi Tila aquifer as follows:

D	<10 m	5	1	=5
R	500 mm	9	5	=45
A	Silts/sands	6	3	=18
S	clay	2	4	=8
T	5%	8	1	=8
I	clay	1	5	=5
C	10 m/d	8	3	=24
				Drastic Index = 113

This assessment highlights the lower drastic index and the lesser groundwater contamination potential of the Dupi Tila aquifer in comparison with other alluvial deposits (Civita, 1990) (Drastic index =202).

However, some factors that in reality affect the vulnerability of the aquifer to pollution do not contribute to this simple parametric analysis. The real situation is much more complex. Therefore, assessment of the vulnerability of the Dhaka aquifer by using field observations, other parameters and modelling is justifiable.

4.8 Summary and Discussions

Heavy exploitation of the Dupi Tila aquifer beneath Dhaka city has led to continuing water level decline and modification of the recharge regime. While the aquifer characteristics are favourable and the borehole designs remain appropriate, the question is how long this situation is acceptable. As Dhaka continues to expand, the aquifer beneath the city may be unable to meet the rising demand of water in future. The stage has already been reached when a decision is needed on the acceptability of relying on depletion storage for further supplies. However, the mechanism of induced recharge provides the key to the question of sustainability. Modelling groundwater flow and solute transport in the aquifer is an essential step in developing the understanding of river-aquifer interaction in Dhaka, which itself is a pre-requisite as a basis for predictions of future piezometric trends and patterns of groundwater flow and quality. The key to resolving uncertainty in the future piezometric trends lies in a fuller comprehension and representation of the river-aquifer interactions. Additional piezometric data from beyond the river boundaries are needed, and a clearer picture of the nature of the physical contact between the rivers, principally the River Buriganga and the aquifer. The hydraulic properties of the river bed sediments are largely unknown. The extent of contact between the River Buriganga and the Bashabo-equivalent sands is also unknown. If faulted contacts mark the limit of the Madhupur Tract then what is the hydraulic effect of the faults?

Induced flow also has implications for penetration of contaminants into the aquifer and for future groundwater quality. These implications are discussed in the next Chapter.

CHAPTER 5 HYDROCHEMISTRY OF THE DUPI TILA AQUIFER

5.1 Introduction

The chemical composition of groundwater results from reaction between water that enters the groundwater system and minerals present in the rock. Groundwater chemistry changes as water moves through the aquifer with chemical equilibrium dependent on the relative rate of groundwater flow and water/rock interaction. Changes may also be due to mixing, for example with leakage entering the aquifer through aquitards and from rivers (Toth, 1984; Runnells, 1989; Winter *et al.*, 1998). The concept of hydrogeochemical cycles helps in the evaluation of the influences of climate, and the geological, hydrological, biological and anthropogenical factors that affect the chemistry of groundwater (Figure 5.1). A geochemical understanding of the processes controlling the natural 'baseline' characteristics of groundwater chemistry forms a starting point from which to study the impacts of anthropogenic factors. It is important that this 'baseline' is understood so that we can recognize what may be deviation from the natural condition. We need to know what the natural or background concentrations of species are, in order to be able to identify the effect of land use including urbanization and waste disposal.

In this chapter, available historical data and the results of previous studies are reviewed. The hydrochemical surveys of the present research are described and an interpretation of the chemistry of groundwater from the Dupi Tila aquifer of Dhaka is presented.

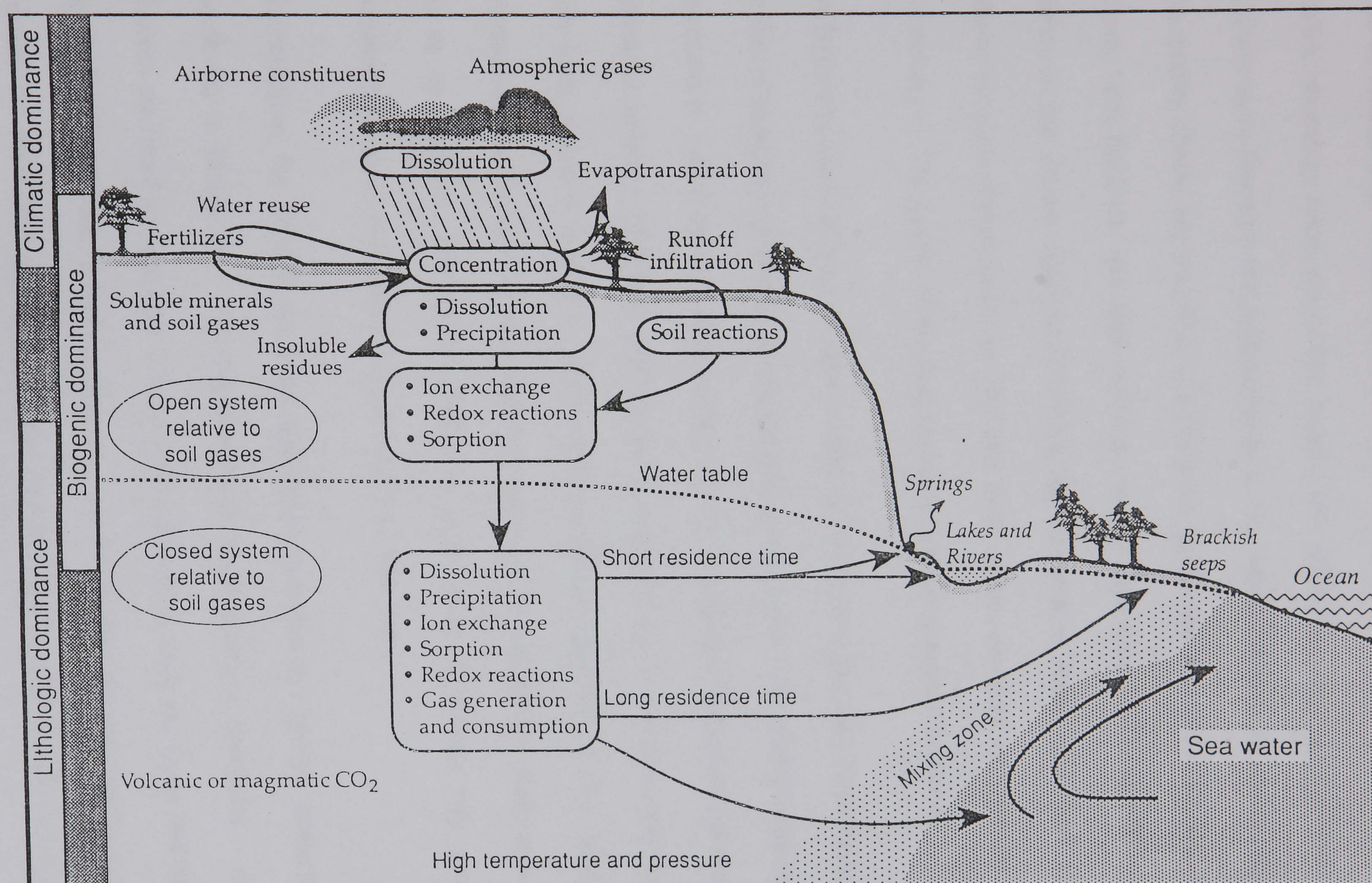


Figure 5.1 *The hydrogeochemical cycle (after Alley, 1989)*

5.2 Previous Studies

There are little pre-existing good quality geochemical data available for the Dupi Tila aquifer of Dhaka city. Water from the DWASA tubewells is routinely analyzed by the DWASA laboratory every one or two months. However, the sampling procedure is poor (e.g. there is no filtration nor acid treatment in the field) and the analysis is only partial so no quality checks are possible. The DWASA laboratory only monitors pH, chloride, calcium, total hardness and total coliforms on an approximately bi-monthly basis. In addition to the routine analysis, DWASA has undertaken some occasional additional analyses for particular purposes in 1988 and 1989. Again, however, only partial analyses are carried out. The quality of the analysis is thought not always to be good.

The hydrochemistry of groundwater within the study area has also been included in a number of independent studies during the past twenty years. The UNDP commented that the results of a widespread hydrochemical survey undertaken by the BWDB with UNDP assistance between 1975 and 1980 produced analyses that were frequently incomplete with ionic contents failing to show electro-neutrality (BWDB, 1980). MMP (1982) commented that the quality of available hydrochemical data for the study area 'leaves a lot to be desired'. EPC/MMP (1991) in their study of Dhaka city groundwater demonstrated that the situation had not improved with time.

Nevertheless, the BWDB has been monitoring groundwater quality annually, at two boreholes in Dhaka city – the Motijheel and Muhammedpur boreholes – since 1974. Results are listed in Appendix 5.1. As for the DWASA analyses, these BWDB analyses are either incomplete or have a very poor ionic balance and may not be reliable. The results are published as BWDB Water Supply Papers (WSP) with some generalised comments but without any geochemical interpretation or graphical presentation. At the Motijheel borehole, chloride and nitrate concentrations have apparently increased over the time of monitoring, and both of these are general indicators of contamination. However, a number of earlier works containing limited analytical results are also worth noting.

Welsh (1966) was the first to report analyses of water samples from DWASA tubewells. He inferred the general EC distribution of wells in Dhaka city at that time, as illustrated in Appendix 5.2. Unfortunately the original individual measurements are not available.

Parsons (1980) collected and analysed some groundwater samples from DWASA wells but the results are no longer available. Alam (1985) analysed 7 samples and concluded that the quality of groundwater in the city is suitable for domestic and industrial purposes. The results are tabulated in Appendix 5.3. GKW (1990) analysed three water samples from DWASA water supply boreholes at Hazaribagh, Armanitola and Baridhara and confirmed that the general quality of water supplied by DWASA is excellent; incomplete analyses only are presented as illustrated in Appendix 5.4.

DWASA (1989) analysed some water samples for the 'Dhaka City Ground Water and Subsidence Study Report' prepared by EPC and MMP, showing higher EC values in the southern part of the city in comparison with the northern part (Appendix 5.5). As for the survey by Welsh (1966) however, the original data point were not recorded.

None of the groundwater chemical analyses for the Dhaka aquifer for the period up to 1992 can be checked for ionic balance because all of them are incomplete. Therefore there must be significant doubt about the quality of the data. The results presented have been examined and the extremely poor ionic balances put great doubt on the quality of the data.

Ahmed *et al.*, (1995) collected and analysed 18 groundwater samples during 1992/1993 from the Dupi Tila aquifer, Dhaka and concluded that the presence of chloride, sulphate and nitrate at higher concentrations in the wells near the Buriganga is indicative of industrial and urban pollution (Appendix 5.6).

Urbanisation commonly results in rising nitrate concentration in shallow groundwater (Nazari, *et al.*, 1993). DWASA analysed 10 pumped groundwater samples (collected during November 1989) from DTWs for nitrate (Appendix 5.7). Nitrate concentrations were apparently all less than 1.0mg/l at that time.

As an objective of the present research, in order to investigate the general trends of groundwater quality, certain wells were selected for re-sampling which have previously been sampled during the past 12 years. Trends in NO_3^- and Cl^- are illustrated in Figure 5.2a and 5.2b. These limited data suggest that the generally high quality groundwater of the Dhaka aquifer shows a trend of deterioration with time.

In summary, there is a lack of reliable hydrochemical information for the Dupi Tila aquifer in Dhaka and nothing is known of the distribution of groundwater quality in detail. Neither is there any comprehensive data regarding trends with depth in the aquifer. To improve this situation it was decided to undertake a thorough hydrochemical study of the Dhaka aquifer especially to investigate variations in the hydrochemistry and the distribution of contaminants in the groundwater.

5.3 Field Surveys and Sampling for the Present Research

Two field surveys of groundwater quality in the Dhaka aquifer were carried out during March to April 1996 and November to December 1997. The physical and chemical parameters of groundwater which are unstable and change over time (pH, alkalinity, dissolved oxygen, electrical conductivity, temperature), were measured in the field. Altogether a total of 110 sites were visited during the two fieldtrips and all the required field measurements were taken in the field.

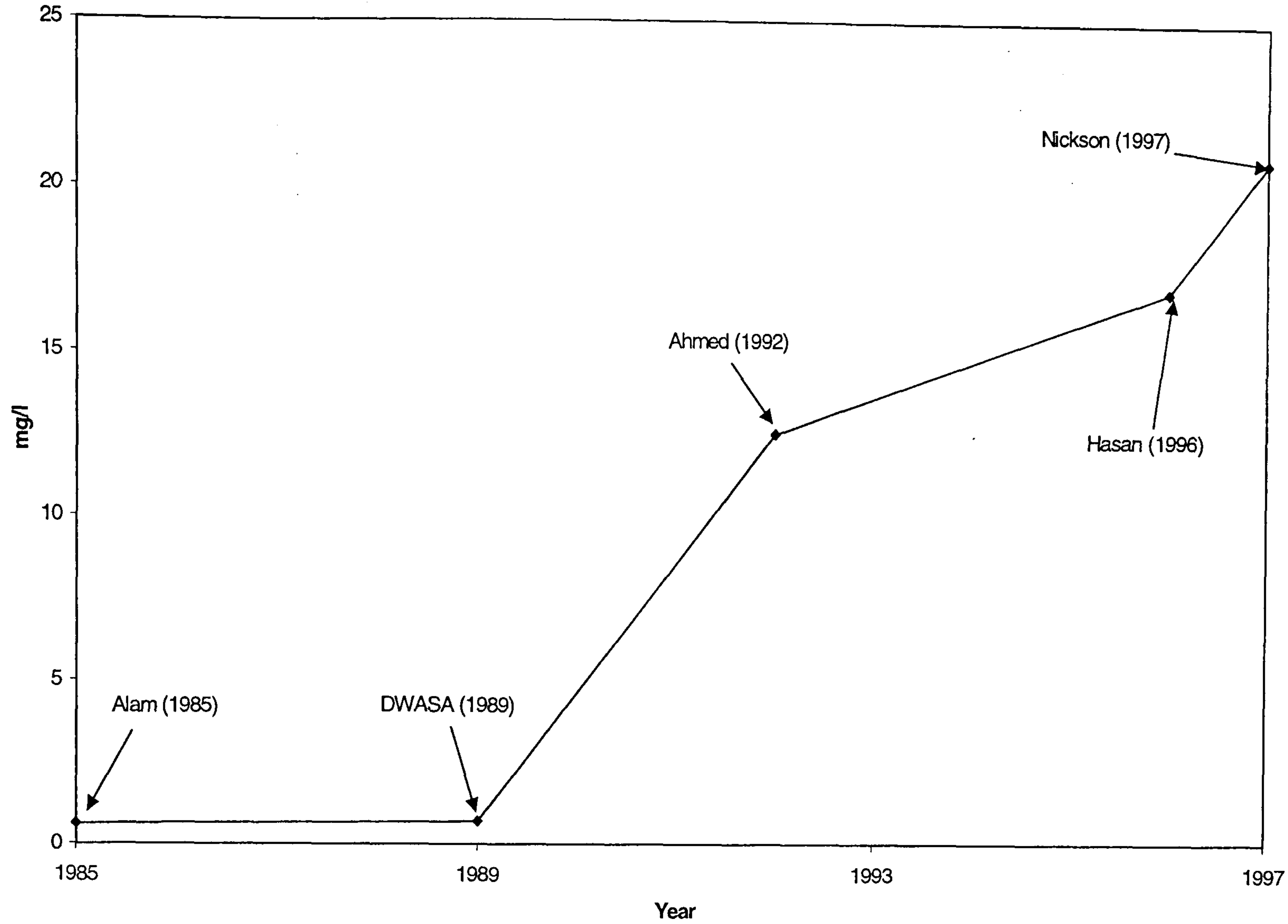


Figure 5.2a *Groundwater quality variation with time, nitrate (Tejgaon well)*

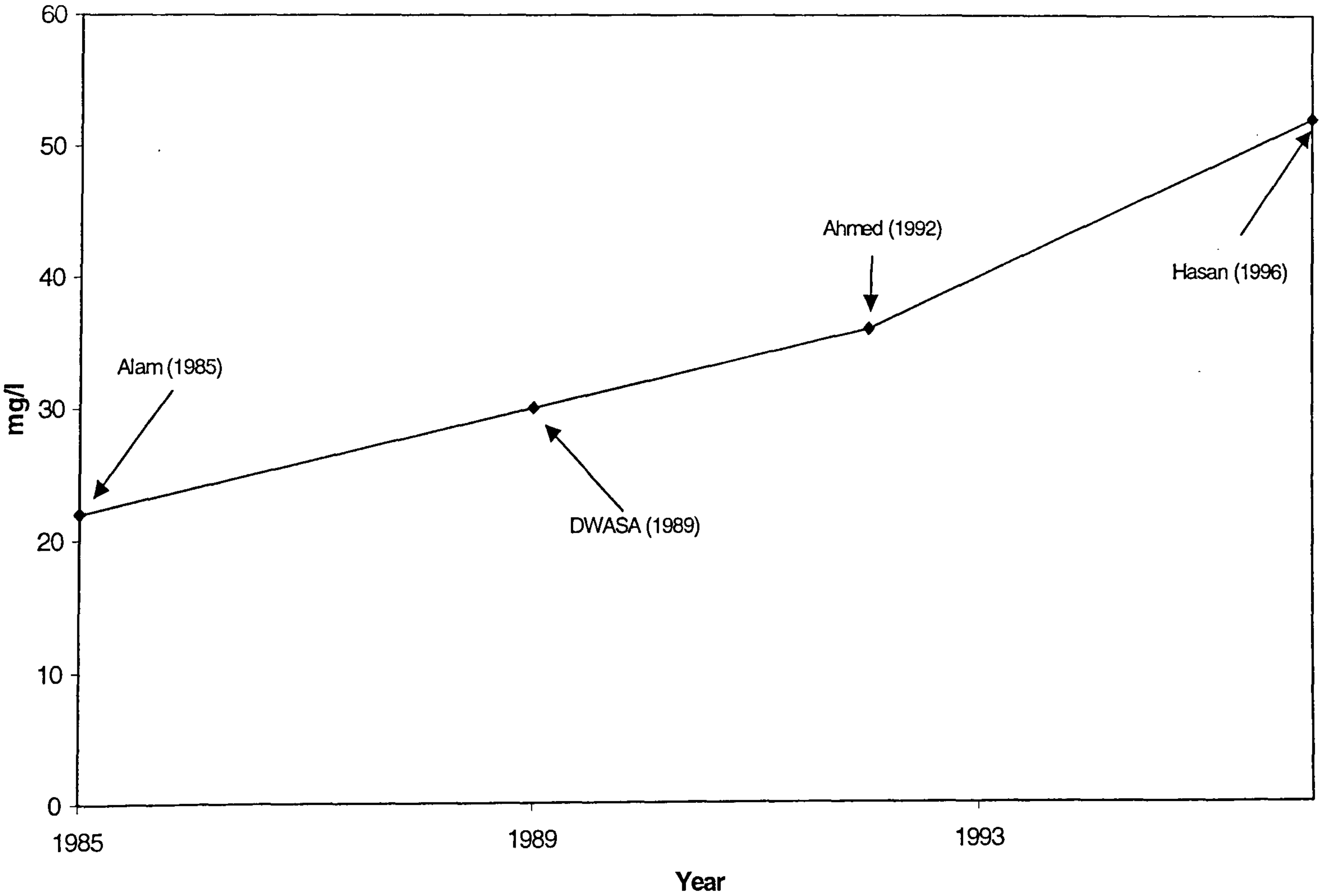


Figure 5.2b Groundwater quality variations with time, chloride (Hazaribagh well)

The first fieldtrip concentrated on the deeper part of the aquifer where the public water supply boreholes are completed. During the second fieldtrip more information was obtained on the shallower part of the aquifer and a further 30 sites were sampled on the opposite side of the Rivers Buriganga (Keraniganj) and Tongi (Appendix 5.8). All the sampling and field test sites are identified on the basemap in Figure 5.3. The field parameters and other necessary sample descriptions were noted down on field sheets. An example field sheet is attached in Appendix 5.9. Furthermore, the relevant hydrogeological information for the sampling sites was collated.

Electrical Conductivity (EC) was determined using a Whatman conductivity sensor that automatically corrects EC to 25^0C.

Dissolved Oxygen (DO) content of the water was measured by using a Jenway Oxygen Meter which automatically corrects for the temperature of the water. Sometimes a flow cell was used during measurement. The meter was calibrated once a week. Temperature was measured using the DO meter temperature probe. PH was determined by using a Whatman pH meter. The temperature corrector was adjusted to the temperature of the water sample before a reading was taken. The probe was calibrated every day by using buffers of pH 4 and 7. A Hatch Digital titrator was used to measure alkalinity as mg/l of HCO_3^- at the wellhead. 50ml of water sample was titrated against 1.6N H_2SO_4 and pH was measured for each incremental addition of acid until an inflection point was passed. A plot of pH against volume of acid added was used to determine the end point of the reaction. The results were used to determine the alkalinity in terms of the concentrations of HCO_3^-. Sampling is an important part of any hydrochemical study and inaccurate sampling can result in erroneous results (Appelo and Postoma, 1993; Mazor, 1990; Hem, 1989; Edmunds, 1986; Lloyd & Heathcote, 1985; Brassington, 1988; Price, 1985).

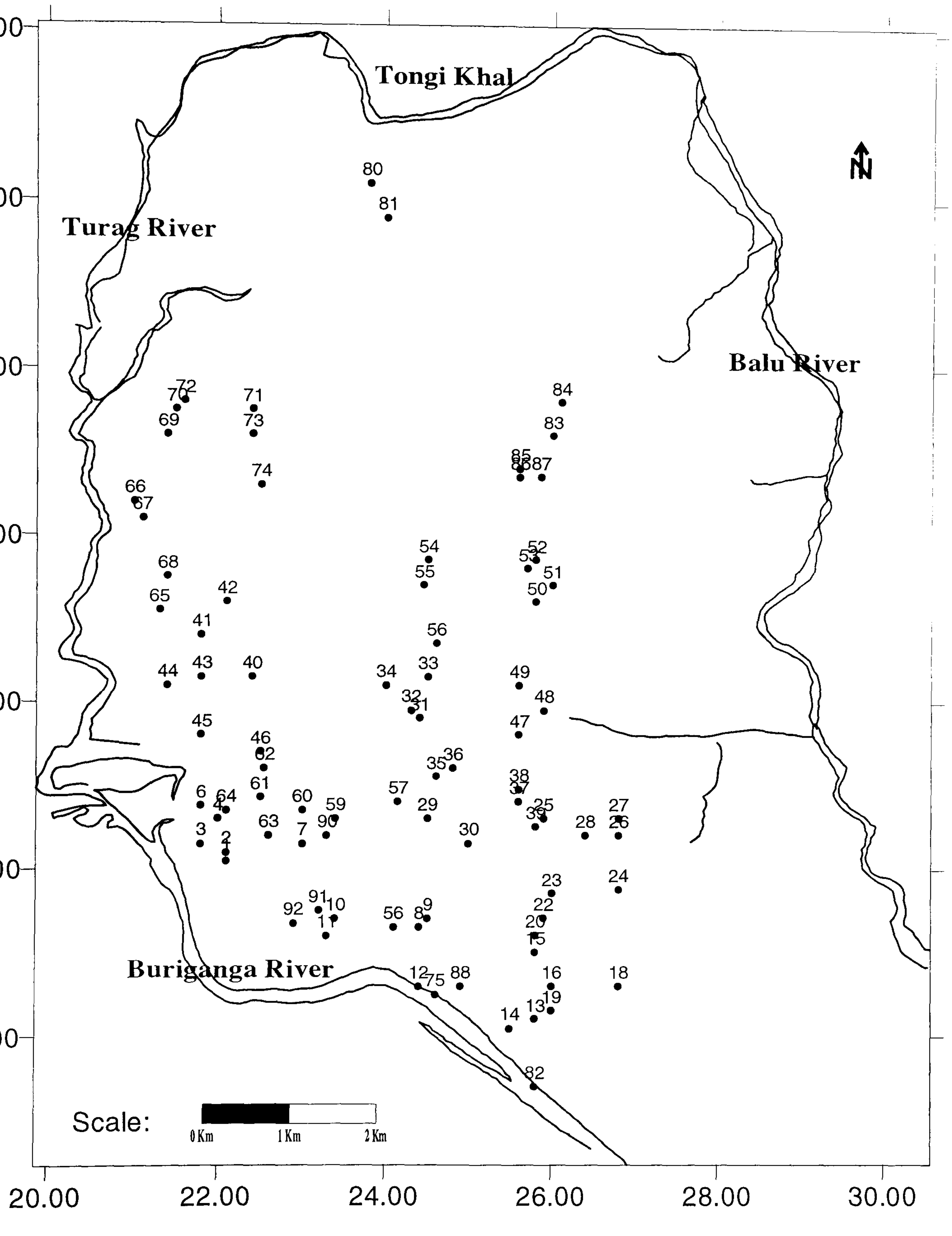


Figure 5.3 Sampling sites of groundwater (DTWs) from the Dupi Tila aquifer, Dhaka (The numbers represent sample number prefixed by KH).

Altogether 113 samples were collected from various parts of Dhaka city during the two fieldtrips. Out of the 113 samples, 82 were collected from pumping DTWs, 29 from HTWs and 2 from surface water bodies. The samples from the DTWs were collected from the sampling tap in line with the discharge pipe. Two types of samples were collected for major ion analysis in separate 25 ml plastic bottles. Both the samples were filtered with 0.45μm filters to remove suspended solids. One sample from each site was acidified with 0.6 N HCl to stabilize ions in solution. All the samples were labelled on-site, sealed in airtight plastic bottles and checked later with the register. The samples were brought back to London for analysis.

A summary of the sample descriptions and field test results is given in Appendix 5.10.

Field Blanks were taken under field conditions every few days using distilled water provided by the Geology Department of Dhaka University, Bangladesh and the Wolfson Geochemistry Laboratory at UCL.

5.4 Chemical Analyses

5.4.1 Methodology

Groundwater samples were analysed at the Wolfson Geochemistry Laboratory at University College London (UCL) and the Natural Environment Research Council (NERC) facilities at Royal Holloway, University of London (RHUL), using the following methods:

A. Anions – Analysis of anions was carried out using **Ion Chromatography (IC)**. A Dionex 2000I IC was used to analyse Cl^-, $NO3^-$, $SO4^{2-}$, and $PO4^-$. When using this method, samples had to be diluted by a factor of five or ten. Samples were filtered using a 0.2μm filter, immediately before injection into the IC machine. The results are given as mg/l, calibrated to a known standard.

B. Cations and trace elements – A PC controlled Phillips PV 8490 **Inductively Coupled Plasma – Atomic Emission Spectrometry** (ICP- AES) was used at the RHUL Geochemistry Laboratory for the determination of major cations Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} and total Fe. Trace constituents were also determined: Al, B, Ba, Cd, Co, Cr, Cu, Li, Mn, Ni, Pb, Sr, Ti, V, Y, and Zn. Detection limits range between 0.1 – 0.001 ppm in the water sample. A standard solution was run after every fifth sample in order to determine the accuracy and drift of the equipment.

C. Arsenic – Analysis of arsenic was done by using **Atomic Absorption Furnace Spectrophotometry (AA)** with detection limit of 5 µg/l.

5.4.2 Results

Results of field measurements are given in Appendix 5.10. Analytical results are tabulated in Appendix 5.11 (major components), Table 5.2 (arsenic) and Appendix 5.13 (trace components).

Groundwater from the Dupi Tila aquifer in Dhaka is generally oxic with low to moderate TDS (150-800 mg/l), dominated by Ca^{+2} and HCO_3^- ions. In some instances Na^{+} is the dominant cation.

Most of the samples in the study area have low to neutral pH (6.0-7.0). Very few groundwaters have pH below 5.0 and above 7.0. The value of the dissolved oxygen content varies between 3 and 70% saturation. The shallow groundwater samples show a fairly uniform range of dissolved oxygen (15-40%) whereas the range for groundwater from the DTWs samples is larger.

5.5 Quality of the Analytical Data

Results of ionic balance checks on the analytical results are given in Appendix 5.13.

The balance can be obtained from the following formula:

$$\text{Imbalance (percent)} = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} *100$$

According to this definition acceptable analytical results should have an ionic imbalance of <3% (Hem, 1989; Edmunds, 1986) or at most <5%- <10% (Lloyd and Heathcote, 1985).

The imbalance is elsewhere calculated as (Karanjac and Braticevic, 1989):

$$\text{Imbalance (percent)} = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} *200$$

An imbalance of <10% is considered acceptable by this definition or 20% with reference to the extreme accepted by Lloyd and Heathcote (1985). This latter method of imbalance calculation has been used in this study. All analyses with an imbalance of <10% have been accepted for interpretation.

The bicarbonate ion, HCO_3^- is the single most contributing ion in almost all the samples and the accuracy in its determination is critical. Measurements of HCO_3^- were carried out in some of the samples in the Laboratory as well as in the field. The field values of HCO_3^- gave better balances in most cases. For some of the samples the cation analyses were repeated before an acceptable balance was achieved.

45 samples (39% of the total) fall well within the limit of acceptability (ionic balance < 5%) and a further 65 samples (57% of the total) fall within the range 5% to 10%. 96% of the samples therefore represent good quality analytical data. The remaining samples with ionic imbalance >10% are considered unacceptable for interpretation. Although all the analytical data are presented in Appendix 5.11, only those with acceptable ionic imbalance <10% have been used for interpretation.

5.6 An Overview Interpretation of the Hydrochemical Analysis

Analytical results have been used for modelling chemical speciation and saturation states using WATEQ4F. Results with reference to saturation indices for representative samples are listed in Table 5.1. In addition, a variety of different graphical methods have been used to illustrate and interpret the Dhaka aquifer groundwater.

5.6.1 Electrical Conductivity (EC) and Chloride Distribution

The electrical conductivity (EC) distribution of groundwater samples in Dhaka city at the time of the 1996/1997 filedtrips is shown in Figure 5.4. A zone of relatively elevated EC (>500 μS/cm) is apparent in the southern part of the city which extends in a band across the aquifer, approximately 10 km long and 5km wide. A similar pattern is apparent in the distribution of specific dissolved components e.g. chloride (Figure 5.5). The spatial distribution of other major constituents is illustrated in Appendix 5.14.

5.6.2 Hydrochemical Facies and Redox Conditions

The use of trilinear diagrams to represent groundwater chemistry was first attempted by Hill (1940) and refined by Piper(1944), Durov (1948), Zaporozec (1972) and Lloyd and Heathcote, (1985). The diagrams are useful in classifying waters and indicating the underlying hydrogeochemical processes and the possibility of mixing.

The term hydrochemical facies is used to describe the bodies of groundwater in an aquifer that differ in their chemical composition. The concept of hydrochemical facies classified using trilinear plots has been widely used since 1950 (Back, 1966). Analyses of the groundwater samples from the Dupi Tila aquifer of Dhaka are plotted on a Piper diagram in Figure 5.6. These waters have no distinct dominant cation. The areal trend illustrates a variable dominance by HCO_3^- at one extreme and Cl^- at the other.

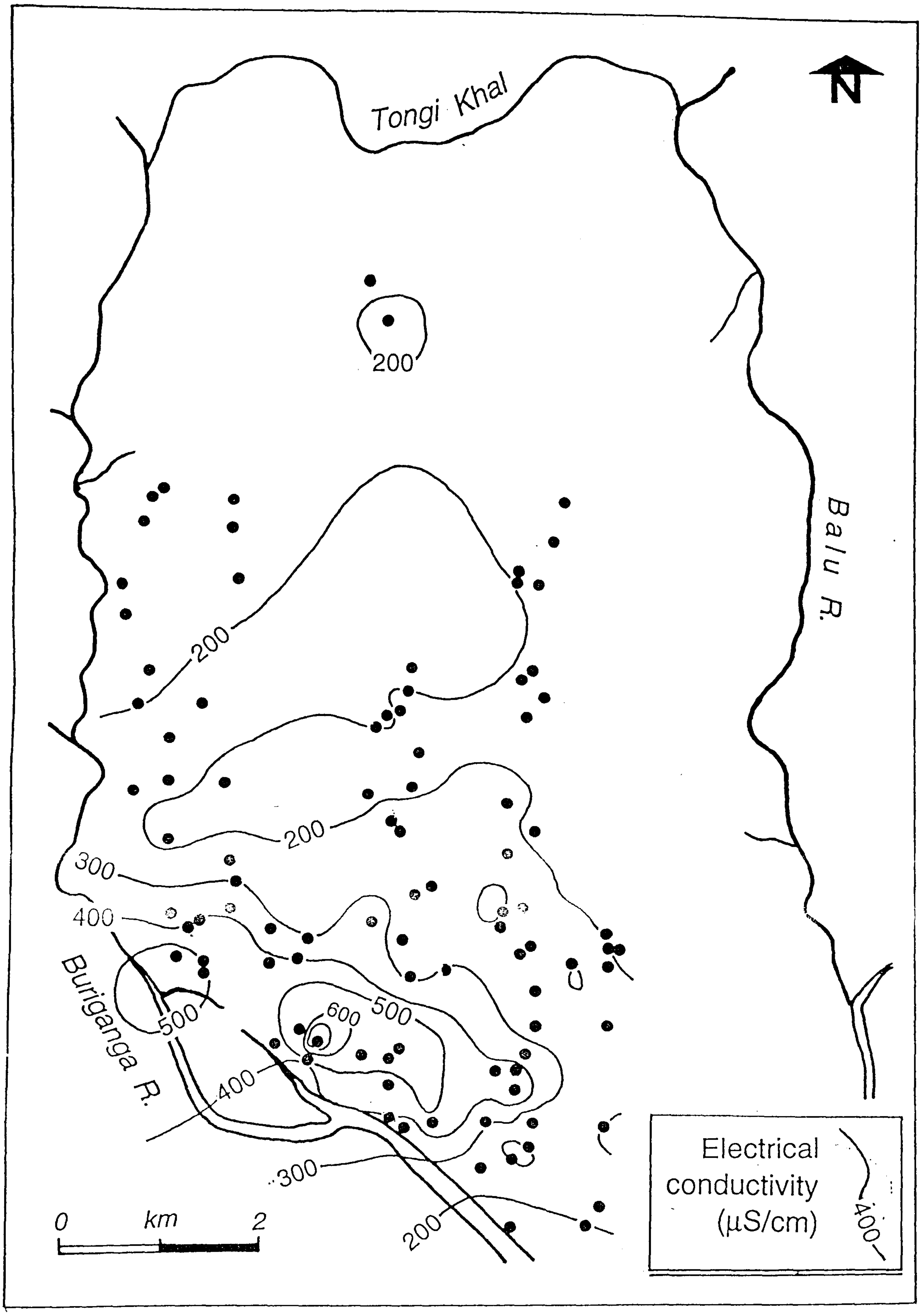


Figure 5.4 *Regional variation in groundwater EC of the Dupi Tila aquifer, Dhaka: Survey of 1996*

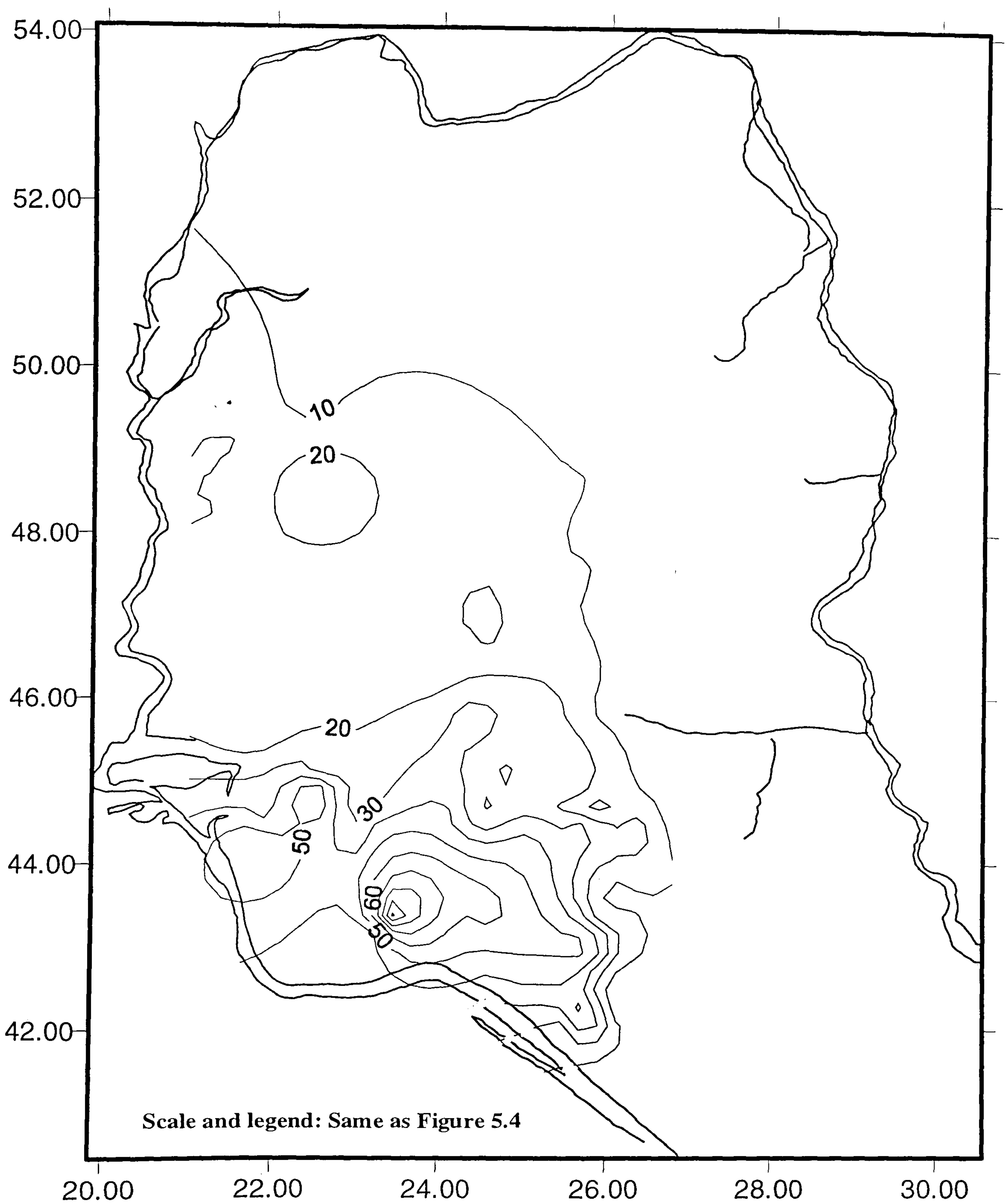


Figure 5.5 Regional variation of chloride (mg/l) in the Dupi Tila aquifer, Dhaka: survey of 1996

The piper diagram shows a linear trend where Ca^{+2} (Mg^{+2}) dominated water is gradually being enriched by Na^{+} and the HCO_3- dominated water is becoming Cl^{-} dominated. This trend is mainly due to mixing but ion exchange can not be ruled out.

Relationships between the redox sensitive parameters dissolved oxygen (DO), nitrate and iron, and between DO and chloride for the upper level of the aquifer and the main aquifer are illustrated in Appendix 5.15. Oxidizing conditions are widespread with DO generally being present at between 10% and 60% saturation in the main aquifer. Instances of high iron concentration are isolated and do not correlate with DO. This indicates some possible errors in the field measurement of DO. The strong inverse relationship between nitrate and iron, however, demonstrates that the aquifer is in general at least sufficiently oxidized to allow nitrate to persist. Occurrences of high iron, >0.25 mg/l, are scattered widely over the city, suggesting that these are isolated instances in both the upper and the main aquifer. The lack of any relationship between DO and chloride further shows that reducing conditions are not associated with the contamination from the river nor the major industrial sites. The lack of relationship between nitrate and chloride under the oxidizing conditions in the main aquifer is inconsistent with them having a common source, but suggests two distinct sources of contamination, possibly the river on the one hand and shallow city-wide sources on the other. In contrast the upper part of the aquifer does show a weak relationship between nitrate and chloride and this shallow level appears more affected by a single type of contamination.

5.6.3 Speciation Modelling

Speciation models calculate thermodynamic properties of aqueous solutions, including the molalities and activities of aqueous species and saturation indices of minerals (Parkhurst and Plummer, 1989). Speciation models can further be used to determine whether water is supersaturated or undersaturated with respect to particular minerals or gas phases. The computer code WATEQ4F (Ball and Nordstrom, 1991; Nordstrom and Munoz, 1994) has been used for this study to determine the chemical speciation and to infer states of saturation with respect to specific minerals and hence to interpret the geochemical processes active in the aquifer system. WATEQ4F is the FORTRAN version of the original WATEQ (Truesdell and Jones, 1973) code which is available as part of NETPATH (Plummer *et al.*, 1991, 1994) and runs on personal computers.

The primary purpose of speciation modelling as used here is to calculate mineral saturation indices, which are indicators of the saturation state of a mineral with respect to a given water composition. The saturation index (SI) is defined as

$$SI = \log IAP/K$$

where SI is the saturation index, IAP is the ion activity product and K is the equilibrium constant for a particular reaction. If the SI is less than zero, the mineral is undersaturated with respect to the solution and the mineral would have a tendency to dissolve. If the SI is greater than zero, the mineral is oversaturated and the mineral has a tendency to precipitate but can not dissolve. A SI of zero indicates that the mineral is in equilibrium with solution and the mineral may not be reacting at all. In practice, SI values between –0.5 and +0.5 are taken to indicate equilibrium.

Saturation indices for selected groundwater samples from the Dupi Tila aquifer were calculated by using the WATEQ4F speciation code. The results show that all the water samples are undersaturated with the minerals calcite, dolomite and gypsum (Table 5.1). In Figure 5.7 the saturation index of calcite has been plotted versus the specific conductance for representative groundwater samples. The results show that the water is undersaturated with calcite. There is no apparent trend towards saturation with increasing TDS; the Dupi Tila groundwater is rather uniform in its carbonate chemistry.

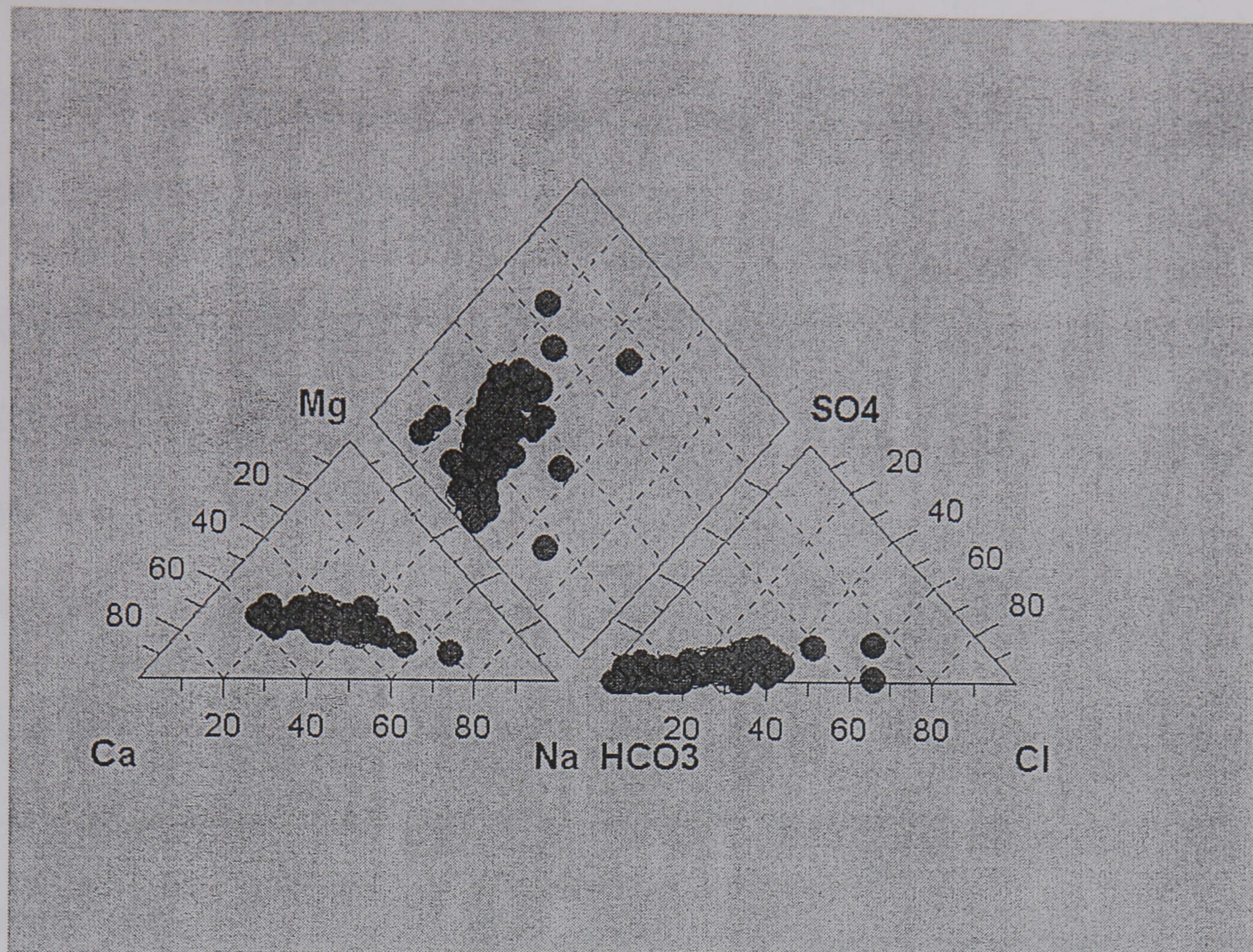


Figure 5.6 Piper diagram of representative groundwater samples from Dhaka city

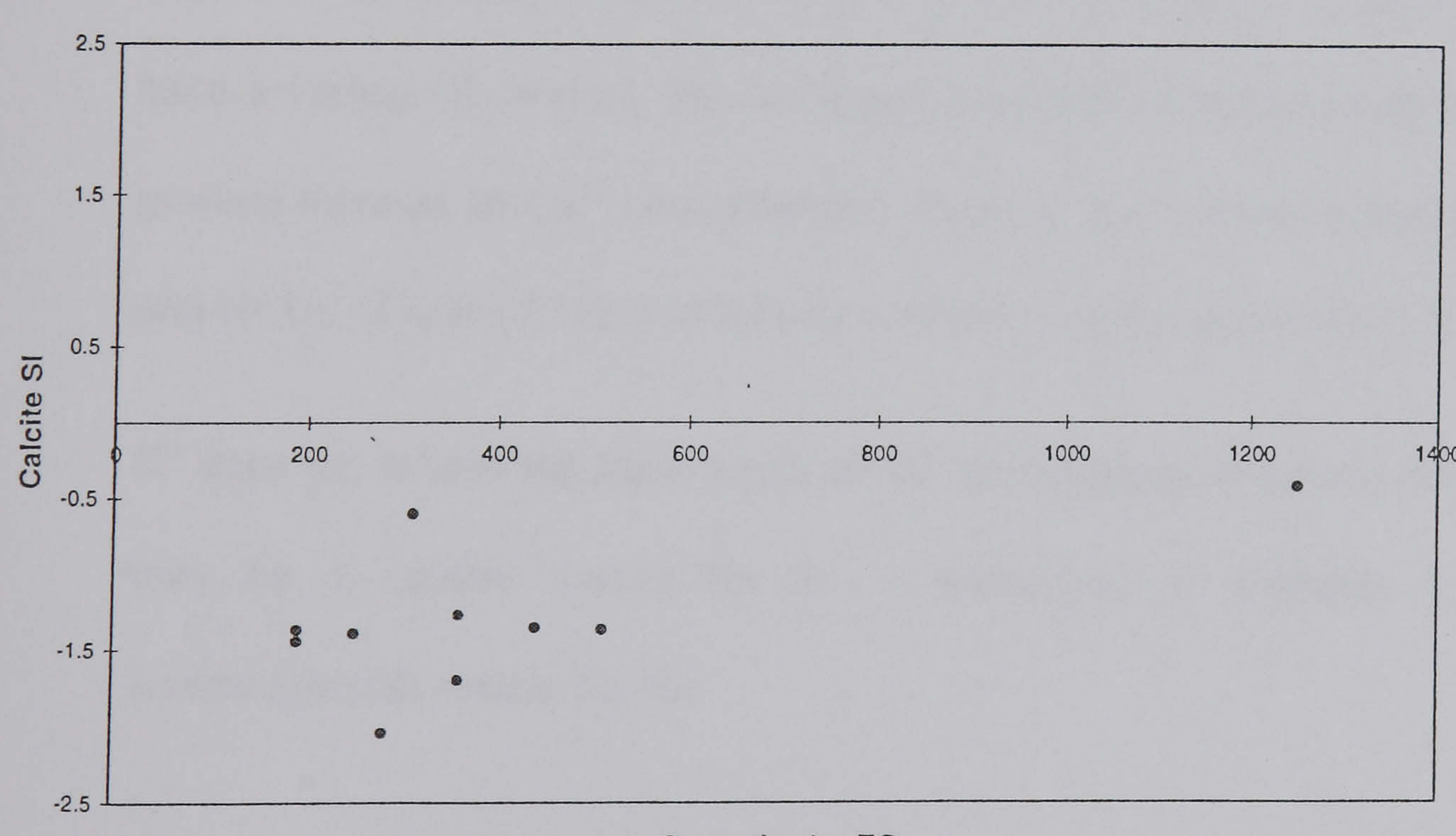


Figure 5.7 *Plot of saturation index (SI) of calcite Vs. groundwater EC of representative water samples from the Dhaka aquifer*

5.6.4 Hydrochemical Relationships

Crossplots of related ions and ionic ratios can be useful in interpreting the geochemical processes within an aquifer (Lloyd and Heathcote, 1985).

A plot of Na^{+} (meq/l) vs. Cl^{-} (meq/l) for the Dhaka aquifer groundwater shows a linear relationship (Figure 5.8), with a Na^{+} / Cl^{-} ration of 1: 1.08. This is an effect either of marine aerosols, or the dilution of a marine connate seawater source with no cation exchange.

Carbonate solubility usually controls the Ca^{+2} and HCO_3^- contents of groundwater even where carbonates are not present in the primary rock mineral assemblage (Freeze and Cherry). The plot of Ca^{+2} Vs. HCO_3^- (Figure 5.9) shows a linear trend of Ca^{+2} increasing with HCO_3^- but with excess of HCO_3^- over Ca^{+2}. The origin of HCO_3^- may be explained by dissociation of $H_2CO_3^-$ in the soil zone, by dissolution of trace amount carbonate minerals and/or redox reaction involving the oxidation of organic matter. Ca^{+2} might have a variety of sources, but carbonate saturation is not reached so does not limit the gradual increase in Ca^{+2} concentration. There is also a linear relationship between Mg^{+2} and HCO_3^- (Figure 5.10), and a fairly constant Ca/Mg ratio of Ca 2:1.

K^{+} does not follow the same trend as Na^{+} and appears to have a different source. There may be a natural source for K^{+} - hydrolysis of feldspar – but an additional (contaminated) source for Na^{+}.

Table 5.1 Saturation index of different minerals in the Dhaka aquifer

Sample no.	Saturation indices (SI)				
	Gypsum	Anhydrite	Aragonite	Dolomite	Calcite
KH-1	-2.45	-2.65	-1.50	-2.77	-1.36
KH-2	-2.57	-2.75	-1.48	-2.77	-1.35
KH-18	-3.00	-3.20	-1.58	-2.93	-1.44
KH-23	-3.70	-3.87	-1.53	-2.83	-1.39
KH-25	-3.63	-3.82	-1.51	-2.85	-1.39
KH-32	-2.70	-2.88	-2.18	-4.17	-2.0
KH-54	-3.62	-3.78	-0.74	-1.25	-0.60
KH-57	-2.52	-2.70	-1.83	-3.51	-1.69
KH-63	-1.73	-1.86	-0.56	-0.91	-0.42
KH-68	-2.50	-1.76	-1.20	-1.30	-1.02
KH-76	-2.63	-2.0	-1.30	-1.60	-1.30
KH-81	-3.60	-3.20	-0.96	-1.26	-0.70
KH-89	-2.73	-2.93	-1.40	-2.53	-1.26

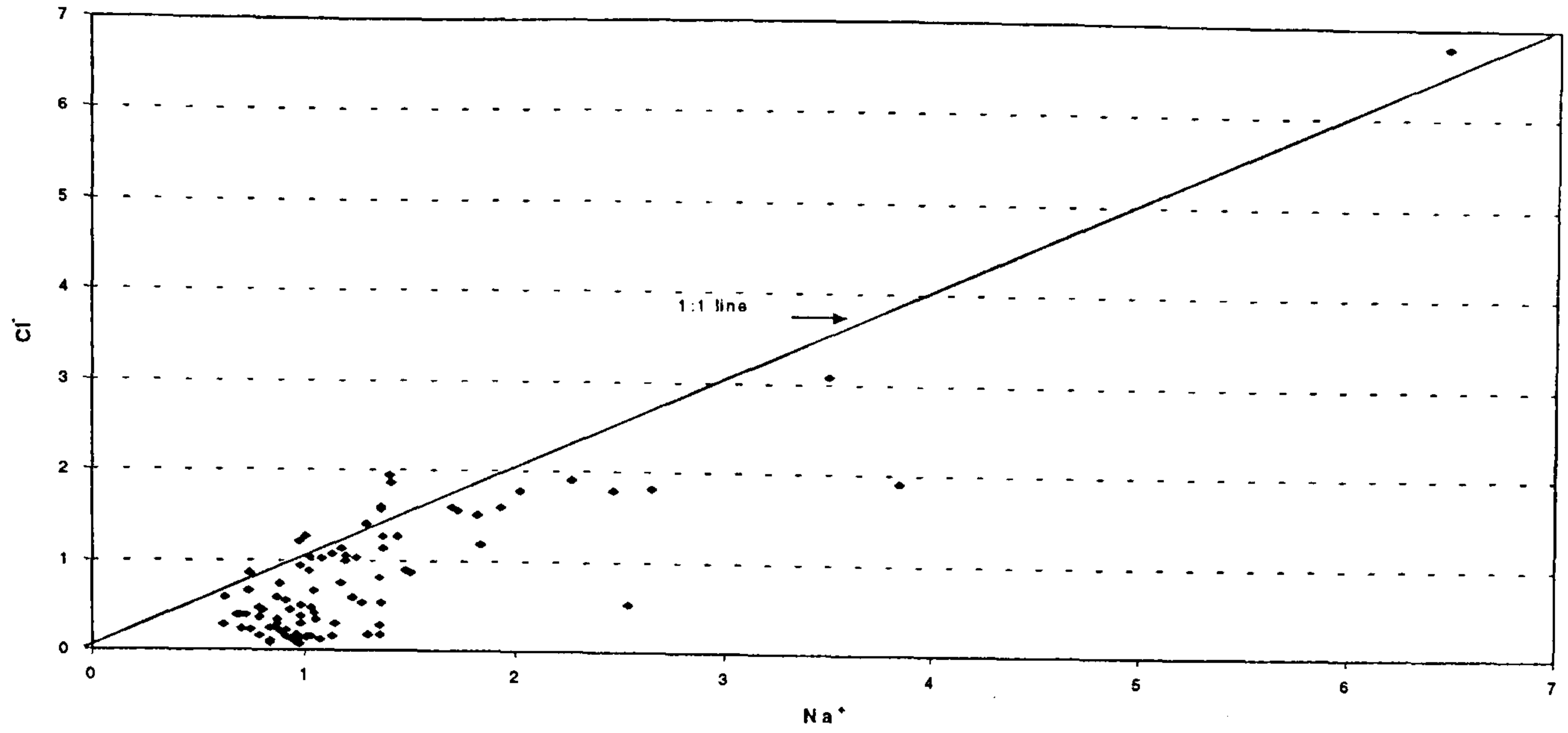


Figure 5.8 *Relationship between* Na^+ *and* Cl^- *of samples from the Dhaka aquifer*

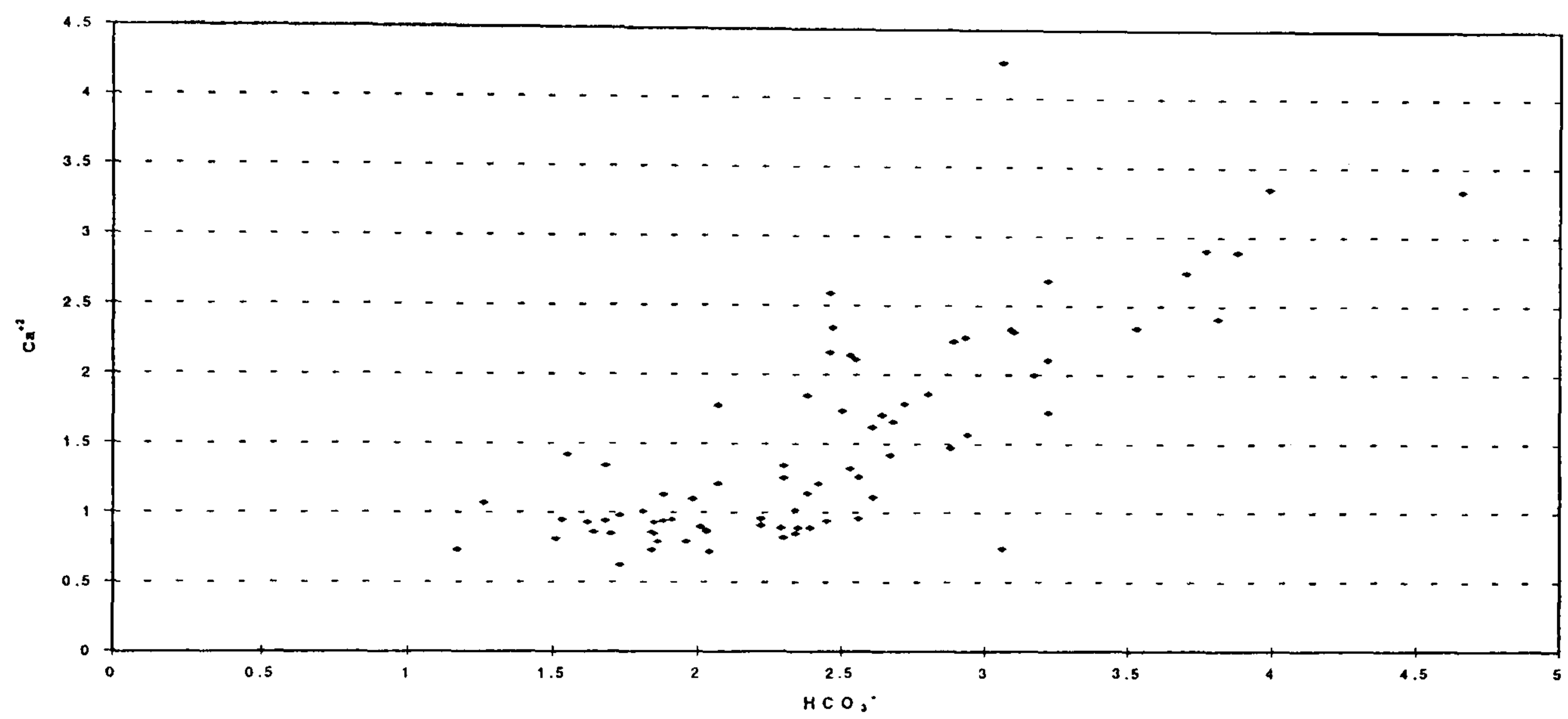


Figure 5.9 *Relationship between* Ca^{+2} *and* HCO_3^- *of samples from the Dhaka aquifer*

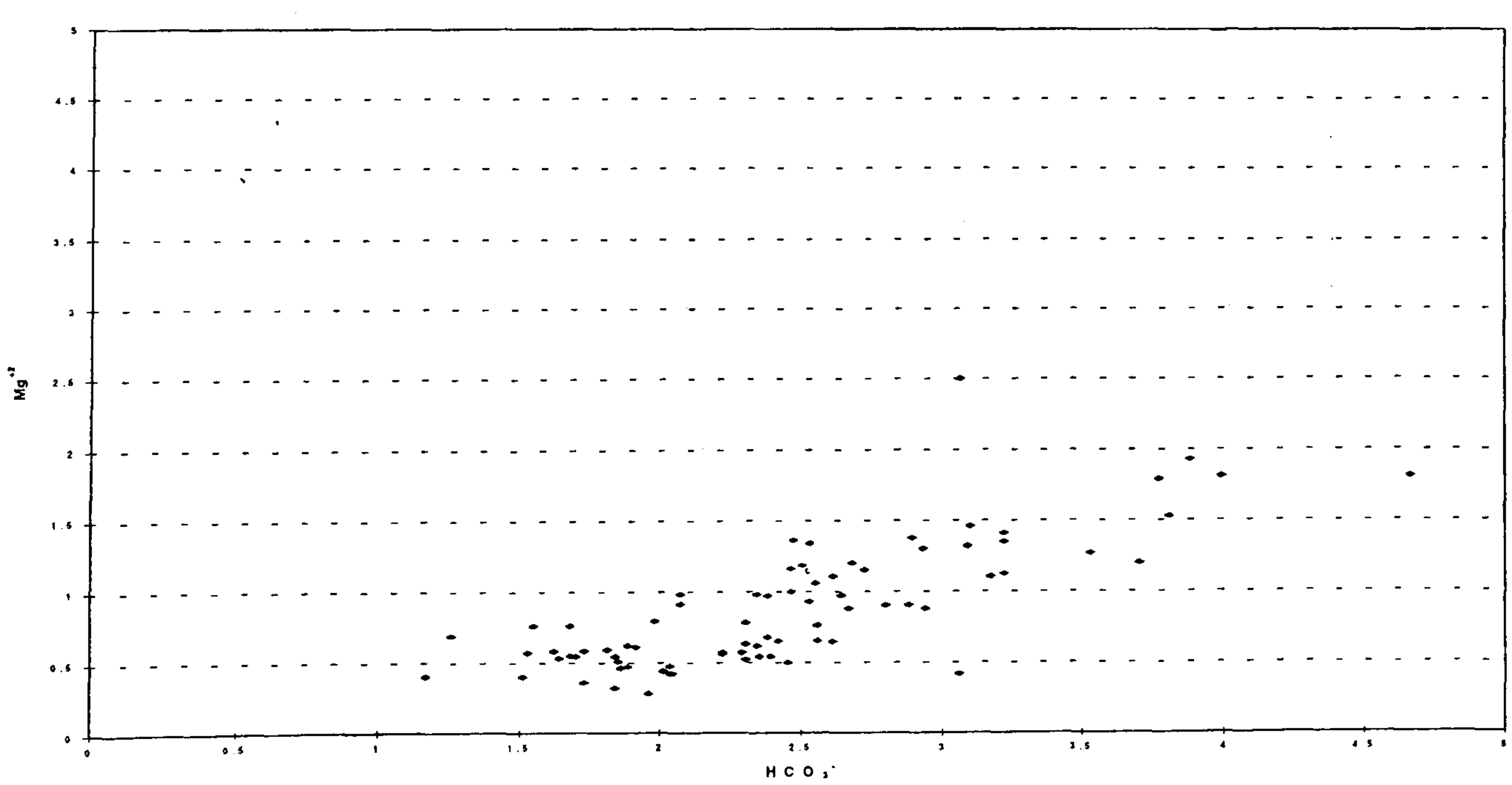


Figure 5.10 *Relationship between* Mg^{+2} *and* HCO_3^- *of samples from the Dhaka aquifer*

* All units are in meq/l

5.6.5 Trace Element Concentration

While this research work was being carried out, severe arsenic contamination of groundwater in Bangladesh received widespread coverage both nationally and internationally. The problem is emerging as the world's biggest environmental health disaster, with more than 200, 000 people poisoned, and tens of millions believed to be drinking arsenic-rich water and therefore to be at risk (Jacobson, 1998; MML/BGS, 1999). At this early stage of delineating the extent of the problem, some of the groundwater samples collected from the Dupi Tila aquifer in Dhaka city were analyzed for arsenic. The results are listed in Table 5.2. The results show that arsenic in the Dupi Tila aquifer is within the provisional WHO 10 μg/l limit. The results are consistent with those of Nickson (1997) who also confirmed that the Dupi Tila aquifer in Dhaka is effectively arsenic free. Arsenic is not a problem in water supplies to Dhaka city.

Heavy metal pollution of surface water and sediments has occurred in Dhaka city as a result of a number of industrial activities associated with the city (DoE, 1993; Karim, 1975; Rahman and Azad, 1995; Shamsuddin and Alam, 1988; Ullah *et al.*, 1995). No study has previously included trace element analyses of the groundwater. The trace element composition of the samples in the study area is listed in Appendix 5.13. Some maximum permissible limits for drinking water (WHO, 1993) are exceeded. All the samples in the study area contain elevated amounts of lead and many samples exceed the limit for drinking water for lead (10μg/l). At Hazaribagh and Mugdapara, the Mn concentration exceeds the WHO limit for the drinking water (50. μg/l) The concentration of Cd is also above the limit in all the samples in Mugdapara area. The minimum , presumed natural condition of trace element concentrations is found in the samples from the northern part of the city, where trace element concentrations are close to zero. The elevated concentrations of Mn, Pb and Cd are centred in the groundwater beneath

Table 5.2 Analyses of groundwater samples from Dhaka aquifer for arsenic

Sample no	Location	Source	Arsenic conc. in mg/l
KHA-1	Tejgaon-9	Pumped DTW	0.008
KHA-2	Nayanagar	Pumped DTW	<0.005
KHA-3	Mirpur	Pumped DTW	<0.005
KHA-4	Dhanmondi-4	Pumped DTW	<0.005
KHA-5	Mugdapara	Pumped DTW	<0.005
KHA-6	Nakhalpara	Pumped DTW	<0.005
KHA-7	Shamoli	Pumped DTW	<0.005
KHA-8	Hazarbagh-4	Pumped DTW	<0.005
KHA-9	BIBM Mirpur	Pumped DTW	<0.005
KHA-10	Armanitola	Pumped DTW	<0.005

the industrial and landfills areas in the city. Despite the clear signature of trace element pollution in groundwater beneath the industrial and landfills areas in the city, the number and concentration of the trace elements in deeper groundwater are not excessively high. The aerobic environment resulting from invasion of oxygen may be responsible for immobilization of some trace metals.

5.7 Baseline Hydrochemistry of the Dupi Tila Aquifer and Indications of Contamination

5.7.1 Natural Evolution of the Groundwater Chemistry

The groundwater in the Dupi Tila aquifer has evolved by a series of reactions that involve the incongruent dissolution of feldspars and micas, and the availability of dissolved organic carbon. Rainwater is the main source of all groundwater in the study area. Due to the low organic contents in the Madhupur Clay a high amount of dissolved oxygen is persists in groundwater of the Dupi Tila aquifer. Flushing of the Pleistocene sediments during the period of low sea level has allowed oxidation of the original organic carbon and ferromagnesiam rich minerals of the Dupi Tila Formation, feldspar hydrolysis has consequently been enhanced. The resultant red-brown iron cements and grey kaolinitic clays reduce the pore space of these sediments (Davies and Exley, 1992). Mica is present in a very weathered orange to clear form, but wood fragments are generally absent. In such a well-weathered formation there is very little material left to buffer the acidity of recently recharged rainwater (Davies, 1994). As a result the groundwaters in the Dupi Tila aquifer are generally of low TDS, mixed cation- HCO_3^- type, with low pH and oxidizing conditions typical of alluvial aquifers elsewhere.

The hydrochemical trends are thought to be dominated by the introduction of low quality water, which results in Na^+ being enriched relative to Ca^{2+} and Mg^{2+}, and Cl^- becoming the dominant anion. This trend would obscure evidence for ion exchange, which may however also be occurring in the aquifer.

5.7.2 Spatial Hydrochemical Trends in the Aquifer

Results of the regional hydrochemical survey of the Dhaka aquifer are illustrated by the EC trend in Figure 5.4. A zone of relatively elevated groundwater EC is apparent in the southern part of the city. A plume of water indicated by an EC greater than 500 μS/cm extends in a band across the aquifer approximately 10 km long and 5 km wide. The likely cause is induced recharge from the polluted river Buriganga. The River Buriganga is polluted by Hazaribagh Tannery effluents, sewage, domestic wastes and hydrocarbon spillage by river vessels (Chapter 2). However, industrial activity is concentrated in this part of Dhaka and the declining groundwater quality may alternatively or in addition be due to polluted urban recharge contributing to vertical leakage through the Madhupur Clay. There has been an apparent progressive migration northwards of groundwater with

EC greater than 300μS/cm since 1966. This follows the northward development of the city with time and may be due to a general decline in the quality of urban recharge. Localised influences of landfill leachate are not apparent at this scale.

The existing EC data also suggest that there was some contamination of the aquifer in the southern part of the city at the early stages of aquifer development as far back as 1966. The progressive northward migration of elevated EC over the past 30 years is shown in Figure 5.11.

The EC of groundwater in the central and northern part of the city, up to River Tongi, is less than 250 μS/cm. This low EC indicates that the aquifer in this part of the city is relatively uncontaminated. However, the area is less developed than the southern part and the groundwater abstraction is much less in comparison.

5.7.3 Vertical Hydrochemical profile in the Aquifer

Marked variation of EC values between HTWs and DTWs is observed in the Hazaribagh and Jatrabari areas. Groundwater EC at the level of the DTWs is lower than at the shallow level of the HTWs in the same areas. This variation is illustrated graphically in Figure 5.12. The average EC value of groundwater from DTWs (depth range 140-160m) in the Jatrabari area is 200 to 300 μS/cm whereas the average EC value of groundwater from the HTWs (depth range 40-70) is 700 to 800 μS/cm. A similar trend is also observed in the Hazaribagh area where the average EC value of groundwater from the DTWs is 500 to 600 μS/cm in comparison with HTWs, which are at 900 to 1300 μS/cm. In Jatrabari, for example, the EC value of groundwater from one DTW is 200μs/cm but the EC value is up to 1400μS/cm at a shallow level very close by. The vertical profiles suggest invasion of the upper part of the aquifer by low quality water from industrial and

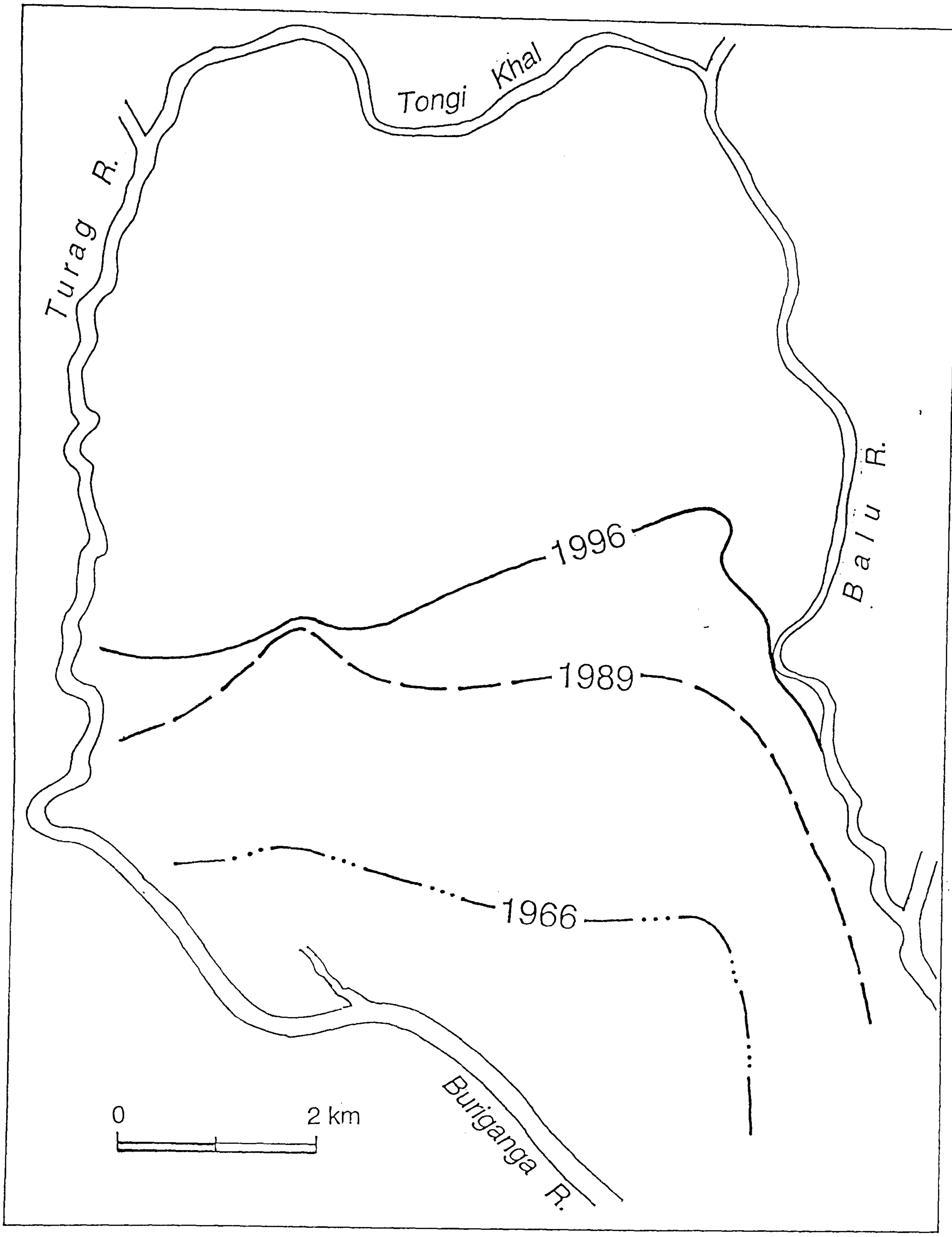


Figure 5.11 *Sequential groundwater quality of the Dupi Tila aquifer, Dhaka (position of 300 μS/cm electrical conductivity contour)*

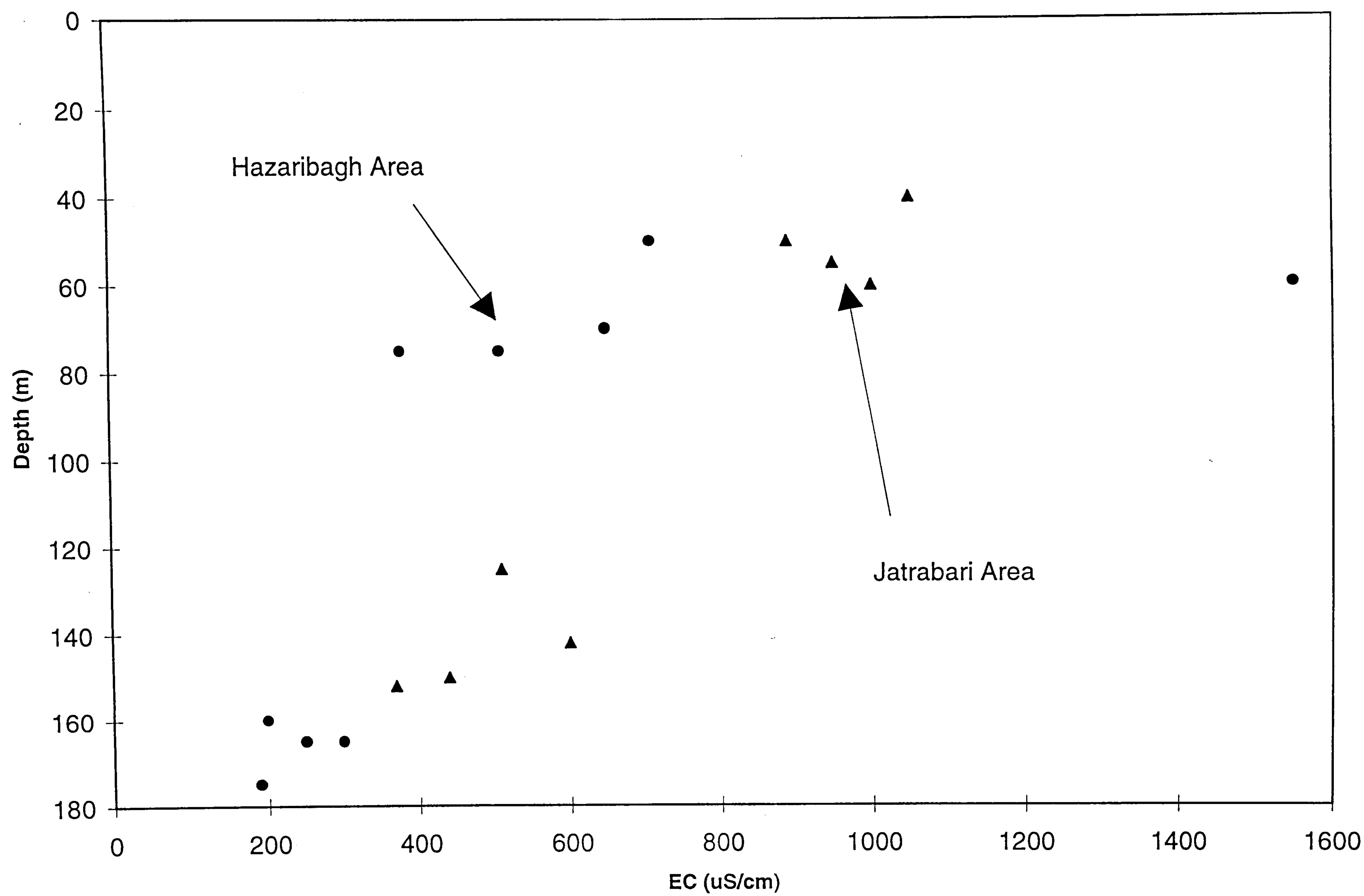


Figure 5.12 Vertical profile of EC in HTWs and DTWs from the Dhaka aquifer

municipal waste disposal sites. In the Jatrabari area this variation may be linked to the abandoned landfill sites of the area. The influence of tannery effluents of Hazaribagh 'khal' on the aquifer of the area is still unknown. In this area the leachate front has probably invaded the shallow aquifer from which the HTWs abstract water. Perhaps the front has not yet invaded the main aquifer from which the DTWs tap water. However, the front might move downward and may invade the main aquifer with time. There is no difference between the groundwater EC of DTWs and HTWs in the Mugdapara area. The landfill leachate of this area may not yet have reached the aquifer, as the landfill site is comparatively new.

5.8 Summary and Discussions

The results of the two regional surveys of groundwater quality in Dhaka city and its environs suggest the effect of induced recharge from the river Buriganga at the southern limit of the city. A distinct zone of lower quality groundwater is apparent in this part of the city, and it has migrated progressively northwards over the past 30 years. The spatial distribution and evolving pattern of the EC in the Dupi Tila groundwater in Dhaka city is most reasonably interpreted as due to a plume of lower quality groundwater entering the aquifer from the river Buriganga. The river is known to be polluted by industrial discharges. The extent of the intruded lower quality water is also coincident with the reach of the river which is most polluted by industrial effluents (DoE, 1993). Whether the effect of pollution has migrated as far as might have been expected in the subsequent 30 years, and the possibility that retardation and attenuation mechanisms are having a significant effect is considered in Chapter 8.

The zone of greatest contamination is also situated directly under the industrial area of Hazaribagh. Vertical leakage of low quality urban recharge in this region, where most of the tanning and dyeing industry is located, may also contribute to contamination of the aquifer.

The shallow wells in these two industrial areas have considerably poorer water quality than the DWASA publics supply wells. There may be further deterioration of the groundwater quality as polluted water in the upper part of the aquifer system moves downward to the main levels of abstraction. The possibility that deterioration in groundwater quality by vertical leakage is minimized by retardation and attenuation is considered in Chapter 8.

The field data shows that the Dupi Tila aquifer may be vulnerable to two distinct types of recharge, but it can not distinguish between their relative significance. This is one important objective of the modelling described in Chapter 7 and 8.

Chapter 6 Reconnaissance Survey to Assess Organic Contamination in the Dupi Tila Aquifer

6.1 Introduction

Contamination of groundwater from a wide range of synthetic organic chemicals is common in industrialized countries (Burston *et al.*, 1993; Lloyd *et. al.*, 1991; Pankow *et al.*, 1996; Rivett *et al.*, 1990; UNEP, 1996; Westrick, 1990; Zoetman *et al.*, 1981). In many cases groundwater pollution takes place almost imperceptibly. Perhaps the most serious threat arises from the chlorinated solvents that are widely used in modern industries. They appear to be ubiquitous in urban groundwater and have been detected in almost all specific surveys (Mackay, 1998). As a consequence of the recent expansion in industrial development in the developing countries, it is probable that chlorinated solvent contamination of groundwater is now widespread in these countries too, yet very few published data are available (Foster *et al.*, 1998; Foster and Lawrence, 1995). The lack of documented cases is likely to reflect the limited study and monitoring which has been carried out rather than the absence of problems. The scale and fate of organic contaminants is generally more difficult to evaluate than inorganic contaminants in groundwater environments. These problems of evaluation result from (1) complexity of field sampling, (2) difficulty of selection and identification of great numbers of possible constituents requiring analyses, (3) operation and maintenance of sophisticated instruments, and (4) complicated and non-unique interpretation of large analytical data sets (using the GC-MS methodology).

The occurrence of inorganic contamination in the Dhaka aquifer has been indicated in the previous Chapter. The likelihood of vertical leakage to the aquifer in the vicinity of industrial areas has been demonstrated. In Dhaka, the general consensus has been that the Madhupur Clay provides a considerable degree of natural protection to groundwater in deep underlying Dupi Tila aquifers (Chapter 4). However, during the past 30 years, industrial activities within Dhaka city have increased substantially (Islam, 1996). There are approximately 450 different types of polluting industries within the city area. Industrial developments are mainly concentrated at Tejgaon, Hazaribagh and Tongi areas (Figure 6.1). Among these industries there are about 160 tanneries concentrated in Hazaribagh area whereas more than 200 chemical, pharmaceutical and other industries are located in the Tejgaon area. The effects of pollution by industrial effluents depend mainly on their nature, composition and the volume of discharge.

The industries in Dhaka city are classified in three groups (Haq, 1989). These are (1) Major polluting industries (11) Moderate polluting industries and (111) and minor polluting industries. The industrial growth in Dhaka city coincided with the development in the use of various organic chemicals for different purposes such as degreasing, processing, cleaning etc. Most of these industries generate liquid effluents such as: spent lubricants, acidic metal rich liquors; solvents; and disinfectants. In Dhaka city, these industries discharge their untreated wastes and effluents directly to the soil or the nearby open water bodies and ditches impounded by the flood protection embankment, which ultimately discharges into the Buriganga River through canals. Consequently, the effluents pose a serious long-term threat to groundwater quality. A further factor is spillage or leakage to the ground by hydrocarbon fuels and liquid chemicals stored in tanks at the industrial sites. Although the surface water and sediments of these industrial sites are already polluted by heavy metal from wastes and effluents (Ullah, 1995; Shamsuddin and Alam, 1988; Karim, 1975) no study has so far been conducted to look at the organic pollution of groundwater. In addition, a large number of landfill sites (Figure 6.1) within Dhaka city is another potential threat and could affect groundwater quality in the city.

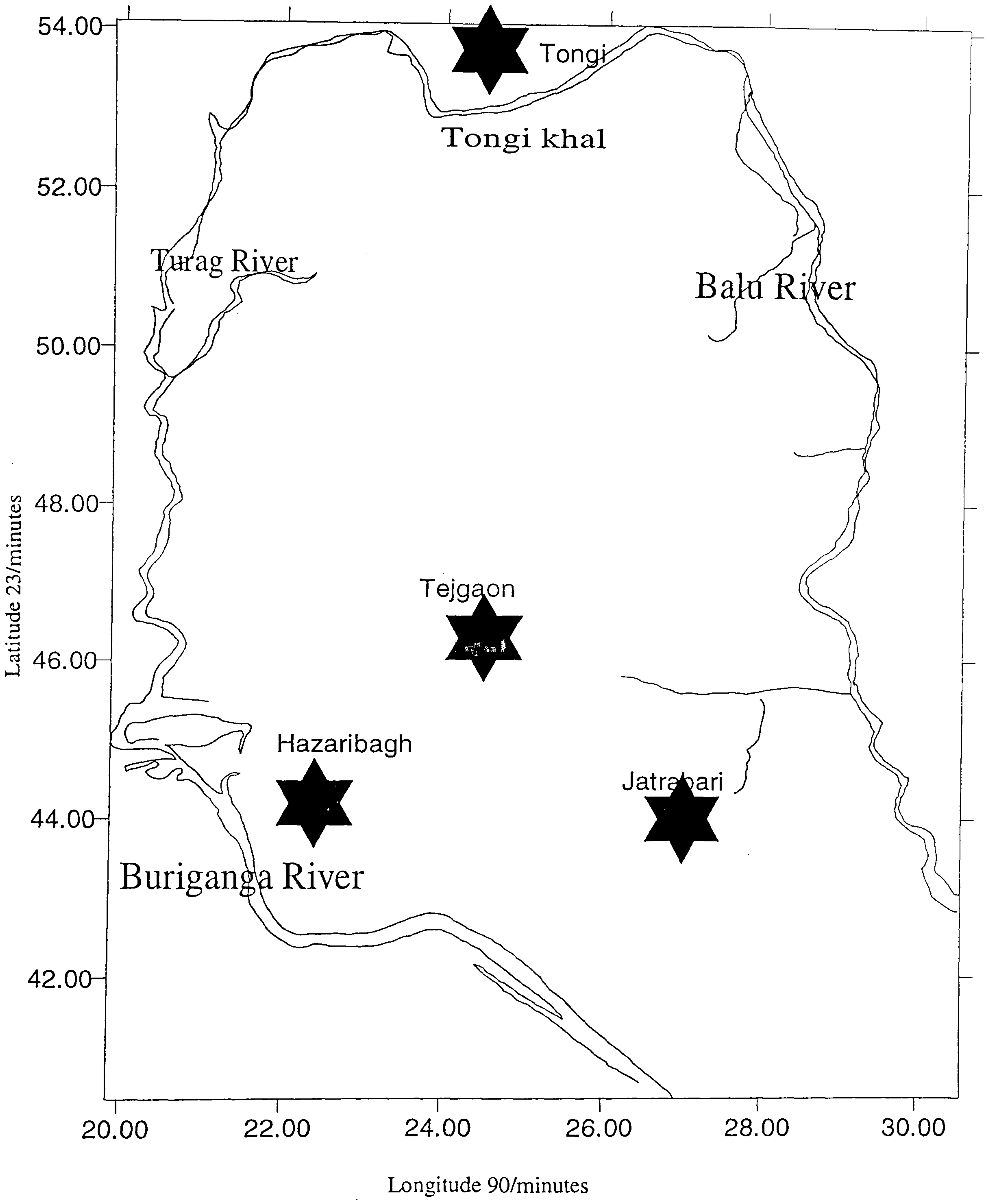


Figure 6.1 Main industrial and landfill areas in Dhaka city

Therefore, the message is clear – in many parts in the Dhaka aquifer there are likely to be organic contaminants, including chlorinated hydrocarbons in the groundwater. It was felt necessary to investigate the organic contamination of groundwater in the Dupi Tila aquifer in Dhaka city. This Chapter describes a reconnaissance survey of organic pollution of the groundwater.

6.2 Sample Collection

Ten groundwater samples were collected from beneath the two main industrial areas, Hazaribagh and Tejgaon, and landfill sites (Figure 6.3) during the fieldtrip of April 1996 for a preliminary reconnaissance of organic contaminants in groundwater. The initial purpose of the sampling was to identify the potential contaminants present in the groundwater samples in the study area. Four of samples were collected from the two industrial areas and six were collected from boreholes close to large landfill sites. All ten samples were collected from DTWs. After analysis of the samples it was felt that a second field trip was necessary to quantify the contaminants identified in the samples. Therefore, during the follow-up fieldtrip another 10 samples were collected from the Hazaribagh and Tejgaon industrial areas. The samples were collected from both DTWs and HTWs. In addition, field blanks (Appendix 5.16) were also collected during the field. All the samples were collected in a 30 ml pre-washed special glass bottle prepared for organic sampling. All the bottles were filled to brim to exclude air, sealed airtight and labelled on-site. The samples from the DTWs were collected from the sampling tap in line with the discharge pipe. The bottle was rinsed with sample at least twice prior to collection. The samples were brought back to London for analysis.

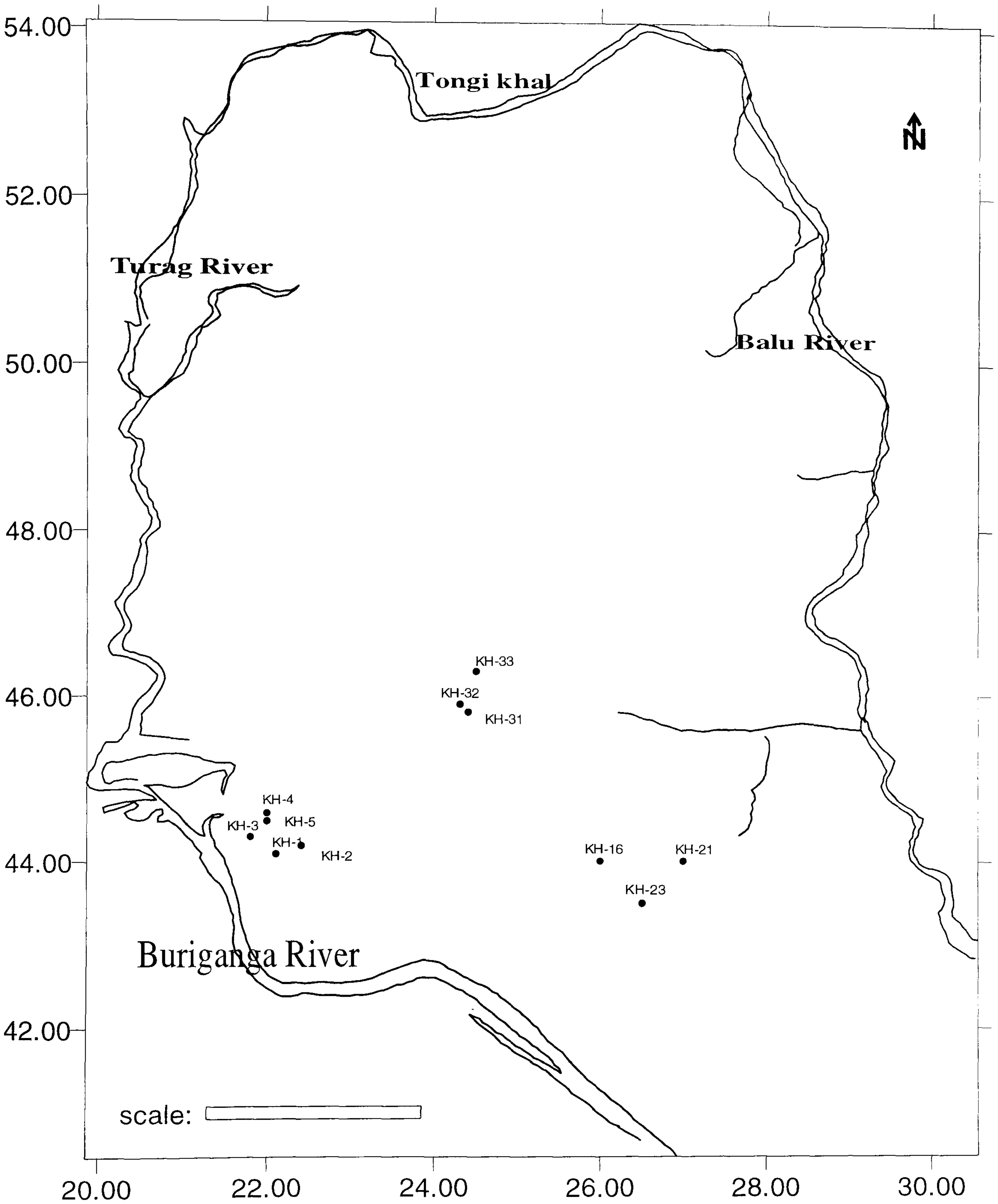


Figure 6.2 Sampling sites of groundwater from Dhaka city for organic analyses

6.3 Analyses - Methodology and Results

Gas chromatography (GC), or combinations of GC with mass spectrometry (MS) are the most commonly used analytical methods for organic compounds dissolved in water. Most of the samples of this study were analysed in the Wolfson geochemistry laboratory at UCL using Gas Chromatography - Mass Spectrometry (GC-MS). Three samples from the second fieldtrip were analysed in the BGS Wallingford laboratory using GC with an electron capture detector. To identify the potential contaminants GC-MS was used for the preliminary samples. Then to quantify the individual contaminants GC was used for the second phase of the samples.

In GC, a mixture of volatile materials is transported by a carrier gas through a column packed with either an absorbing solid phase or an absorbing liquid phase that is coated onto a solid material. The volatile component partitions between the carrier gas and the absorbing phase and the length of time that it takes for the component to traverse the column is characteristic. If there are several compounds in a mixture the column will separate them and they arrive at different times (Fetter, 1993). In MS, the compound is ionized by an electrical discharge and the ions are then separated based on their charge - to - mass ratio. The output is a mass spectrum, which can be compared to the mass spectra of a large number of standard compounds stored in an electronic database called a mass spectra library. The GC/MS combines the resolving power of capillary GC with the sensitivity of MS and is one of the most useful analytical techniques available today. The technique is useful because it enables the separation, quantification and most importantly identification of the many components present in a sample.

The US EPA has developed a series of standard methods for the analysis of organic

Table 6.1 US EPA 600 series analytical methods for organic compounds

Method Number	Analytical Technique	Target Compounds
601	GC	Purgeable hydrocarbons
602	GC	Purgeable aromatics
603	GC	Acrolein and acrylonitrile
604	FIDGC	Phenols
605	HPLC	Benzidines
606	GC	Pathalate ester
607	GC	Nitrosamines
608	GC	Organochlorine pesticides and PCBs
609	GC	Nitrosamines and isophorone
610	GC and HPLC	Polycyclic aromatic hydrocarbons
611	GC	Haloethers
612	GC	Chlorinated hydrocarbons
613	GC/MS	2,3,7,8-TCDD (dioxin)
624	GC/MS	Purgeable organics
625	GC/MS	Acid and base/extractable organics

chemicals dissolved in water. These are known as the "600 series" methods. Table 6.1 lists the 600 series and the target compounds. A "Purge and trap" procedure was used in the samples to isolate volatile organics. Helium is bubbled through a column of water containing dissolved organics, so that the organics are purged from the water and carried with the helium gas. The organics are then trapped on Tenax, a solid sorbent. The tenax is then heated and the volatile organics are swept into a gas chromatography column for separation, and then detected. The results are reported as volatile organics or purgable organics. This method is called method 624.

Not all the organic compounds are purged from the water by the helium gas. These are the semivolatile compounds. Solid Phase Micro Extraction (SPME) is a method that is more appropriate for the semivolatiles, as used in USEPA method 625.

The method used by Wolfson laboratory is based on USGS open file report 94-708. The procedure is described in detail in the Appendix 6.1. Results of the preliminary identification and subsequent analyses of contaminant concentration are given in Table 6.2 and Table 6.3 respectively, and two chromatograms are reproduced in Figure 6.3.

Table 6.2 Organic pollutants detected in groundwater samples from Dhaka aquifer

Borehole type	Location	Depth	Contaminants detected	Possible source
Deep Tube Well	Tejgaon	150	PCE, TCE, benzene	Industry
Deep Tube Well	Tejgaon	140	TCE, chloroform	Industry
Deep Tube Well	Tejgaon	160	TCE and PCE	Industry
Deep Tube Well	Hazaribagh	180	PCE, and benzene	Industry
Deep Tube Well	Hazaribagh	140	PCE and TCE	Industry
Deep Tube Well	Hazaribagh	180	TCE, Chloroform	Industry
Deep Tube Well	Hazaribagh	165	PCE and xylene	Industry
Deep Tube Well	Mugdapara	150	Nothing is present	Landfill
Deep Tube Well	Jatrabari	165	Nothing is present	Landfill
Deep Tube Well	Jatrabari	150	Nothing is present	Landfill

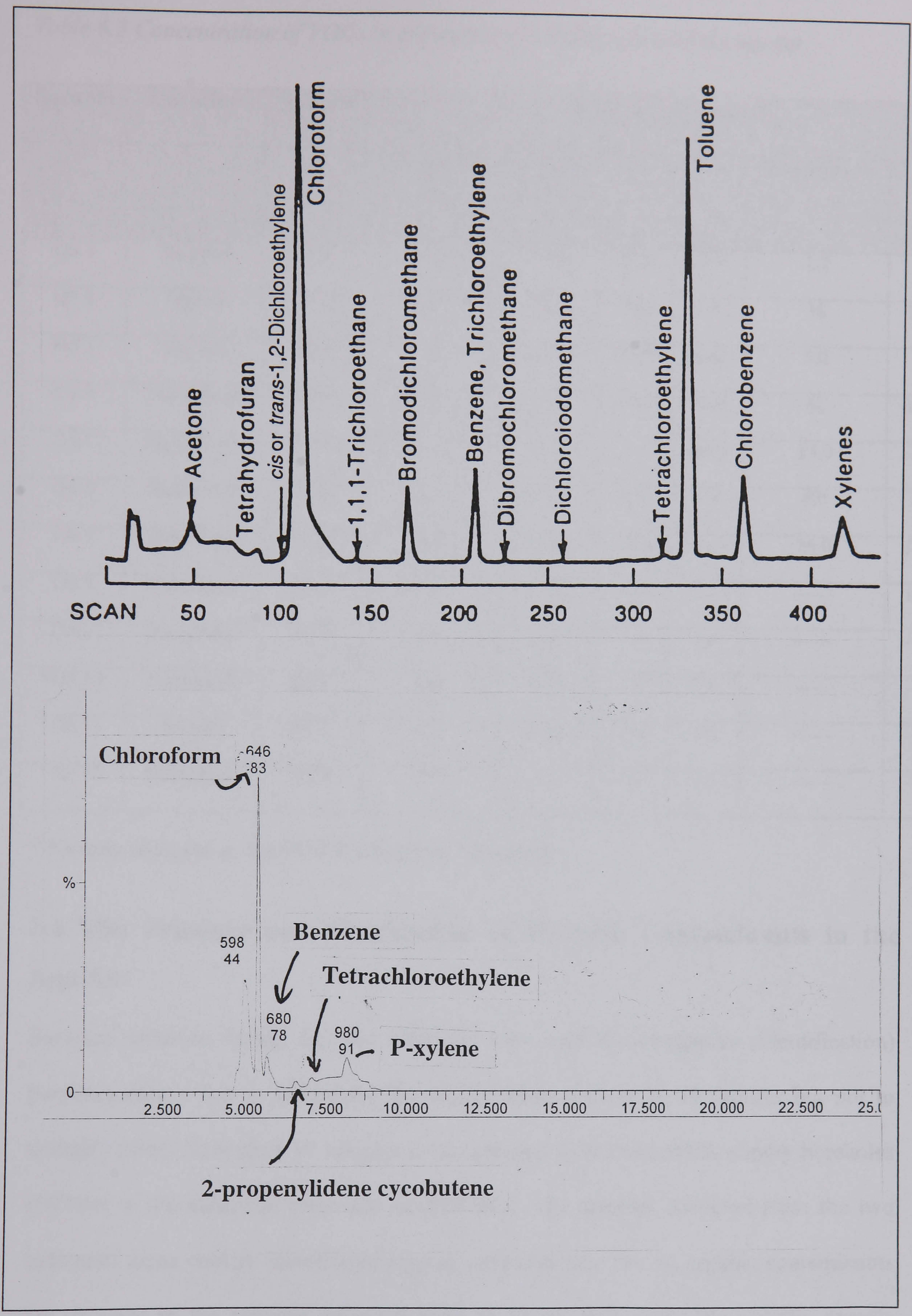


Figure 6.3 *Chromatogram of organic sample, Typical chromatogram identifying volatile chemicals (top), Chromatogram of a sample from the study area (bottom)*

Table 6.3 Concentration of VOCs in groundwater samples from Dhaka aquifer

Sample	Location	Source	Concentration µg/l					
			Chloroform	Benzene	TCE	PCE	Ethylbenzene	Total xylene
OS 1	Tejgaon	DTW	1.2	0.5	32.0	12.0	1.7	3.0
OS 2	Tejgaon	DTW	3.0	15.0	20.0	1.0	38	124.0
OS 3	Tejgaon	DTW	5.4	-------	15.0	trace	5.0	16.0
OS 4	Hazaribagh	DTW	7.6	12.0	29.0	trace	42	159.0
OS 5	Hazaribagh	DTW	-------	1.1	2.1	trace	13.0	31.0
OS 6	Hazaribagh	DTW	3.0	Trace	2.7	-------	6.0	24.0
OS 7	Hazaribagh	HTW	4.0	7.2	14.0	-------	26.0	100.0
OS 8	Hazaribagh	HTW	-------	------	------	------	------	trace
OS 9	Hazaribagh	HTW	1.0	trace	1.2	1.0	------	------
*OS 10	Dolaikahal	DTW	2.0	---------	1.5	2.5	------	------
*OS 11	Tejgaon	DTW	1.0	trace	2.5	3.6	------	------
*OS 12	Hazaribagh	DTW	2.0	------	1.8	2.7	------	------

* Sample analysed at the BGS Wallingford laboratory

6.4 The Presence and Distribution of Organic Contaminants in the Aquifer

Samples collected during the first field trip were used for qualitative (identification) purposes only - that is to identify the contaminants present in the aquifer but not to quantify them. Altogether 10 samples were collected only from public supply boreholes (DTWs) in the industrial areas and landfill sites. The samples collected from the two industrial areas contain identifiable organic contaminants, but no organic contaminants are presents in the samples collected close to the landfill sites. The volatile organic compounds (VOCs) chloroform, perchloroethylene, p-xylene and benzene have been identified in the public supply boreholes from both the Hazaribagh and Tejgaon industrial areas. The presence of other compounds such as bromobenzene, chlorobenzene, methyl-ethyl benzene, trimethylbenzene, toluene were also been tentatively identified in the samples. During the second field trip most of the samples were collected only from the Tejgaon and Hazaribagh industrial areas where the presence of contaminants have been identified in the first field trip. Some HTW samples were also collected from the Hazaribagh area to identify the contaminants in the shallower part of the aquifer. By necessity most of the HTWs were located some distance (up to 1000m) from the contaminated public supply wells. Results are listed in Table 6.3.

The distribution of VOCs indicates that pollutants contaminate both the shallower and deeper part of the aquifer but no depth trend could be found. The more toxic, water-soluble, and mobile components of petroleum hydrocarbons such as benzene, toluene, ethylbenzene and xylene (BTEX compounds) have been identified from all the samples. However, apart from benzene the concentrations of these components are low. Benzene is the only hydrocarbon found in the groundwater samples which exceeds the WHO (1993) limits for drinking water (10 μg/l). In general, the BTEX compounds degrade relatively rapidly, especially in aerobic condition. As the Dhaka aquifer is aerobic, BTEX compounds would not be expected to be persistent in the aquifer. Toluene and xylene are in general more degradable in this environment than benzene and ethylbenzene (Deutsch, 1997).

On the other hand, chlorinated hydrocarbon solvents are known to be highly resistant to biodegradation and are persistent in the subsurface environment, particularly in aerobic condition. Chlorinated solvents TCE and PCE had been identified in the public supply boreholes from Dhaka aquifer. However, the concentration of TCE is higher than PCE. As the chlorinated solvents (DNAPLS) are denser than water so any free phase present may penetrate the aquifer to depth and could provide a continuing source of contamination to the groundwater until it completely dissolves.

6.5 Discussion

Limited analysis of groundwater samples from Dhaka clearly indicates that groundwater in the Dupi Tila aquifer, particularly beneath the industrial area, is polluted by industrial solvents and some hydrocarbon fuel components. It is also found that the concentration of some of the pollutants, for example, benzene and TCE already exceed the WHO limit for drinking water in the Dhaka aquifer.

As a result of heavy abstraction the piezometric surface in the Dupi Tila aquifer has been significantly lowered. Substantial leakage through the unsaturated Madhupur Clay now represents an important component of groundwater recharge and is responsible for carrying organic pollution into the aquifer. However, the slow movement of water from the land surface through the Madhupur Clay to deep aquifers means that it may be many years after a chemical first enters the ground before it affects the quality of groundwater supplies. The subsurface migration of Non-Aqueous Phase Liquids (NAPLs) is rarely controlled by the conventional transport mechanisms of advection, dispersion and diffusion; discrete non-aqueous phase liquids can penetrate underground in a highly heterogeneous manner. However, it is important to distinguish between pollution of the aquifer, which would suggest widespread contamination, from pollution in the vicinity of a tubewell which could be more localised. How did the organic pollutants reach to the deeper groundwater? Possible pathways for organic contaminant migration to a DTW are as follows.

1. Deep penetration through the Madhupur Clay as vertical leakage of dissolved phase or as DNAPL free phase
2. Contamination via abandoned wells - Polluted surface water may flow into and down abandoned wells and directly contaminate the aquifer. This route effectively by-passes the upper Madhupur Clay layer of the aquifer system where maximum attenuation and retention can be anticipated.

Having considered the pathways of pollutants it is clear that only the most mobile and persistent compounds are likely to penetrate to the deeper aquifers. The presence of BTEX compounds at such a depth is unusual. Therefore, it is believed that the source of the BTEX compounds may be very close to the sampled borehole and it may be the DWASA abandoned wells in the area that are responsible for this BTEX pollution in groundwater.

Yet despite the severity of the sources of pollution, the Dhaka aquifer appears remarkably resilient. The oxidizing environment may allow degradation of hydrocarbon contaminants. Hydrocarbons degrade much more rapidly under aerobic conditions that anaerobic condition. However, the oxic environments in the aquifer may slow down the rate of natural attenuation of DNAPL contaminants. The possibility of attenuation during leakage through the Madhupur Clay may be partially responsible for lower concentration of organic pollutants in the deeper groundwater. In addition, once urban recharge reaches the water table, hydrodynamic dispersion of contaminants in groundwater flow would dilute persistent and mobile pollutants. Further mixing and dilution will take place in the flow towards the water supply in the production wells. Although the concentration of chlorinated solvents in the Dhaka aquifer appears to be relatively low, the volumes pumped out of the boreholes used for sampling are large and the aquifer may have small areas of gross contamination. If the concentration of TCE is only 30 μg/l then on average each borehole pumps out about 95kg/annum TCE.

In conclusion, it can be confirmed that various organic pollutants are present in the Dupi Tila aquifer in Dhaka city. The presence of organic contaminants at both the Tejgaon and Hazaribagh industrial areas demonstrates the importance of vertical leakage through Madhupur Clay towards the aquifer. The source of the chlorinated hydrocarbon compounds is believed to be effluent from tannery and chemical industries. However, the inevitable time lapse between sampling in Dhaka and analysis in London might be responsible for the lower concentration of the pollutants detected in the samples. On the other hand, the effect of degradation, adsorption, attenuation may be responsible for the lower concentration that is currently unknown.

The presence of organic contaminants of serious environmental concern in the Dupi Tila aquifer of Dhaka has been established by this reconnaissance survey. The results of the survey also raise concerns regarding the security of groundwater quality within the city in the longer term, and point towards the need to assess in more detail the impact of urbanization on organic contamination of the aquifer. Further more focused work regarding the organic pollution in the Dhaka aquifer is required to establish the source and extent of the contaminants.

CHAPTER 7 MODELLING GROUNDWATER FLOW IN THE DHAKA AQUIFER SYSTEM

7.1 Introduction

7.1.1 Background and previous modelling

Three groundwater models have been developed in the past to assess the groundwater resource availability in the Dhaka city region. RMP/Montgomery first developed a groundwater model for Dhaka WASA in 1980, Solomon and Chidley reviewed this model in 1986, and lastly in 1989, Engineering and Planning Consultants/ Sir Mott MacDonald and Partners. (EPC/MMP, 1991) developed the Dhaka region groundwater and subsidence model for Dhaka WASA. In 1995, a strip model was developed along the River Buriganga by Bhuiyan (1995). These models are discussed briefly below:

- **RMP/Montgomery (1980) (The Parsons Model)**

This model was developed for DWASA to assess the impact of additional groundwater abstraction on the Dhaka aquifer system. It was a finite difference model and the aquifer system was simulated as a single aquifer unit overlain by a semi-confining layer. Aquifer transmissivities were specified in the range of 1800 to 2400 m^2/d. Natural recharge to the aquifer system was separated into two components, subsurface recharge and river recharge although it is not clear what is meant by subsurface recharge. The study area was delineated by the major rivers surrounding Dhaka and river recharge was specified as an input for those model nodes that were associated with major rivers.

The model was calibrated against historical data, whereby model parameters were modified to obtain an acceptable match between observed and simulated aquifer response to pumping.

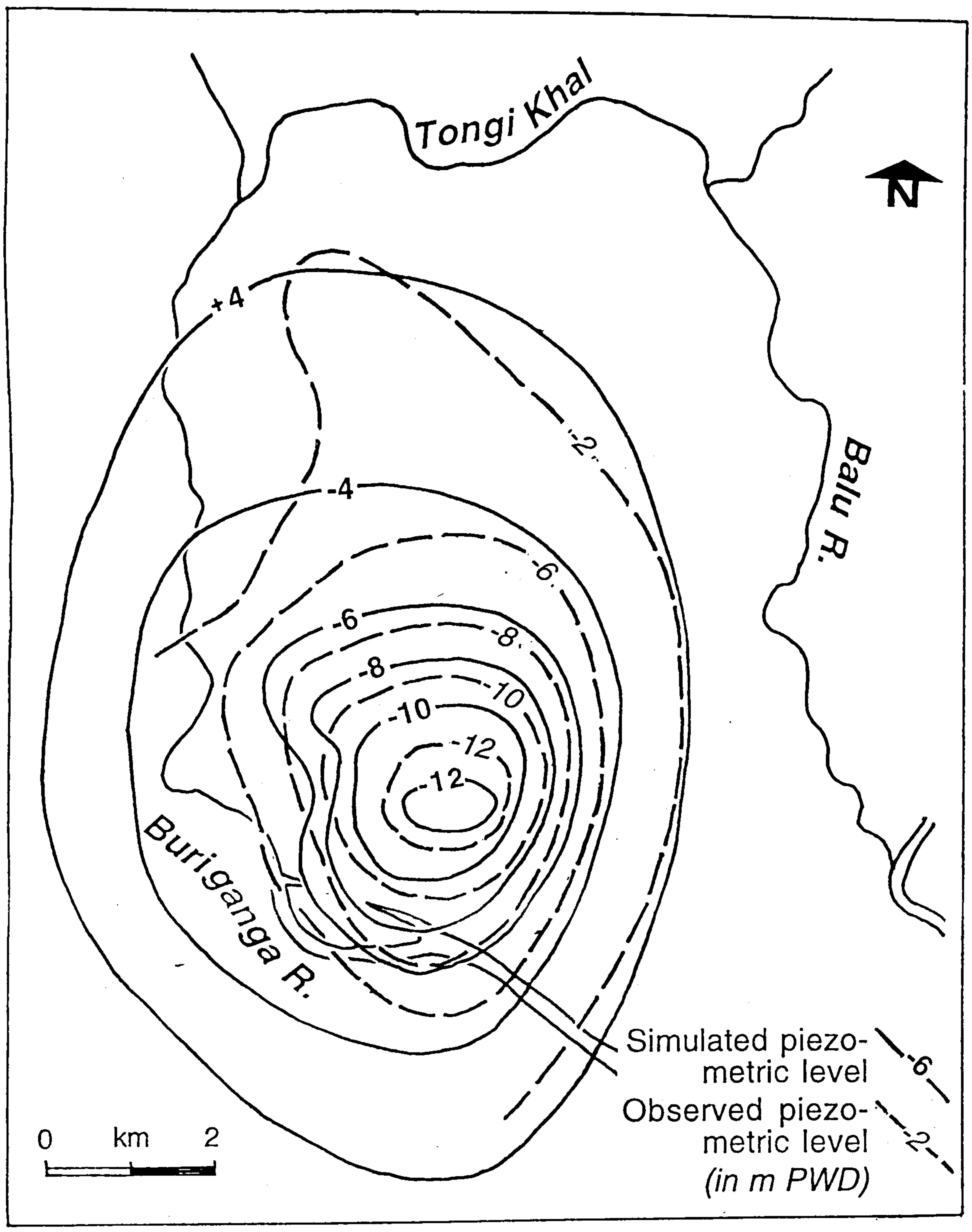
The results of the model show a clear weakness in the simulation of contribution of major rivers to the aquifer. The model did not allow for an increase in river contribution with increased abstraction and as a consequence, simulated drawdowns are overestimated. The model lacks the necessary detail to accurately simulate the interaction between rivers and the aquifer system (EPC/MMP, 1991).

- **Solomon and Chidley's Review of the Parsons Model (1986)**

The limitations of the Parsons Model, as described by Solomon and Chidley, were poor representation of the boundary conditions and recharge mechanism. Solomon and Chidley reviewed the Parsons' model to reassess the groundwater resource, considering the effect of rivers and the potential recharge values from the Master Plan Organisation (MPO), and hydrogeological parameters from the Bangladesh Water Development Board (BWDB) study of the Dhaka District. Two prediction runs were made. Results showed similar future drawdowns to those predicted by Parsons. The model was not calibrated against historical data. It was concluded that more detailed modelling of Dhaka city was necessary, with special emphasis on extending the model boundaries to the major rivers and improved simulation of recharge mechanism.

- **Dhaka Region Groundwater Model (1991)**

- This model was started in 1989, with the purpose of assessing the impact of 50 new and 10 replacement tubewells. A basic feature of the model is the resolution of three-dimensional groundwater flow into its horizontal and vertical components. The model was based on the integrated finite difference method (Narasimhan and Whiterspoon, 1976). The modelled area is bounded by three major rivers, the Jamuna, Ganges and Meghna on three sides and the northern boundary is defined in places by the Old Brahmaputra and elsewhere by the northern edge of Gazipur and Manikganj districts. The groundwater resources model consists of two integrated



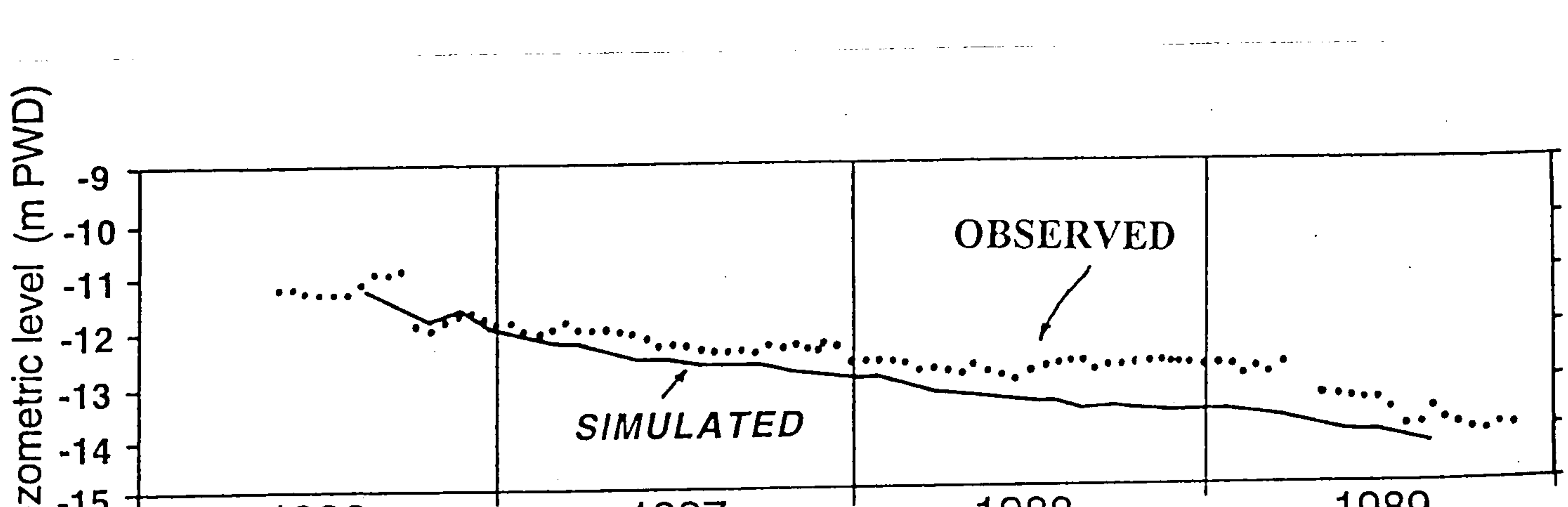


Figure 7.1*. Simulation of the Dupi Tila aquifer piezometry for 1986 (top) and the Motijheel borehole water level (Bottom), 1986-1989 (after EPC/MMP, 1991)*

units. The regional model evaluated the consequences of groundwater development on a regional basis. The Dhaka sub-model considered the Dhaka Metropolitan area and its immediate surroundings in detail. The Buriganga river was represented by internal boundary elements along the side of 1.3 *1.3 km grid cells. The model is sufficiently refined to take into account the spatial variability of such parameters as local relief, geology, physiography and the distribution of abstraction.

This was a four-layer model, consisting of: the lower aquifer (main aquifer of abstraction), the lower aquitard, the upper aquifer and the upper aquitard. The flows are simulated as horizontal in aquifers and vertical in aquitards. Both steady and transient state flow are simulated by the model. The geometry of the aquifer system is defined by the elevations of top and bases of different layers. The model achieves a good calibration with available historical piezometric data (Figure 7.1).

- **Strip Model for Dhaka City (1995)**

Bhuiyan (1995), in his MSc thesis, modelled a strip area of Dhaka city along the bank of the river Buriganga. He simulated saturated-unsaturated flow in three-dimensions by using Galerkin's finite element method. The simulated domain is composed of 4 layers: upper aquifer, upper aquitard, lower aquifer and lower aquitard. The calibration of the model was very limited, but a sensitivity analysis of some parameters was performed. The boundary conditions of the domain were derived from the river water level and observed piezometric level data. Simulated water balance components identify the river effect as the most dominating recharge mechanism of the area which contributes around 60% of the total volume of abstraction.

7.1.2 Purpose and logistics of modelling

The aims of the current modelling are

- To update and modify the existing models of groundwater flow in Dhaka CityTo evaluate the impact of increased groundwater abstraction on the groundwater balance in the city area.
- To assist in understanding the recharge mechanism and groundwater flow in the Dupi Tila aquifer in Dhaka.
- To serve as a basis for modelling solute (dissolved contaminants) transport in the aquifer system.
- To identify any requirements for further management and monitoring of groundwater resources.

The methodology followed was to

- Retain the knowledge incorporated within the EPC/MMP groundwater flow model (EPC/MMP, 1991).
- Modify and process the EPC/MMP model input data for MODFLOW so as to be able to extend and update the model to allow solute transport under conditions relevant to the present day and the foreseeable future, and
- Use MT3D (Zhang, 1990) for simulation solute transport in the groundwater system, to explore the vulnerability of the aquifer to contamination.

7.2 Data Collection and Interpretation

7.2.1 Sources of Data

Data requirements for the model were obtained from various reports and organizations, given below:

- The general geological and hydrogeological data were collected from previous reports, e.g. Salahuddin, 1990; EPC/MMP, 1991. A large body of data assembled for the Dhaka region groundwater model by EPC/MMP for DWASA was used in an advanced state of interpretation, by permission of the Mott MacDonald Ltd (MMP), UK. The incorporation of that data is described in relevant sections below.

- Borelogs, pumping test results, and abstraction data were obtained from Dhaka WASA
- Water level monitoring records for boreholes were collated from the BWDB. The BWDB are also the source of information on groundwater and river levels.
- Recharge data were collected from MPO and MMP.
- Data related to boundary conditions such as river level, bed elevation etc. were collected from BWDB, Surface Water Modelling Centre (SWMC) of MPO, and MMP and re-interpreted as necessary.

7.2.2 Geology and Aquifer System Geometry

Geology:

The geology of the area has been studied in detail by using DWASA and BWDB borehole logs and has been described in Chapter 3. A summary of the Pliocene to Recent stratigraphy and hydrogeology is given in Table 3.2. Dhaka lies at the southern end of the Madhupur Tract, a fault-bounded uplifted block of Pleistocene sediments. At the surface across the uplifted Tract is the Madhupur Clay, which is up to 45m in thickness (an average of 10m thick in Dhaka) and has a fine sandy member at its base. The term Madhupur Clay is widely used for the sequence of tough, over-consolidated, reddish-brown to grey silty clays that occur at the surface of the Madhupur Tract. Drainage channels and shallow depressions on the Madhupur Tract are partially infilled with grey and yellow organic - rich sands and clays of the Holocene Bashabo Formation. At the margins of the Madhupur Tract are the Recent flood plain deposits of the Rivers Turag, Buriganga, Balu and Tongi.

The Madhupur Clay overlies fine to coarse-grained micaceous, quartzo-feldspathic sands of the Dupi Tila Formation. These sands are approximately 140m thick in Dhaka. At the top of the Dupi Tila Formation are fine silty sands, which grade downwards into fine/medium-grained sands, and medium/coarse-grained sands with gravels towards the base. There are appreciable amounts of iron oxides and secondary clays as weathering products of the original mafic minerals throughout. Clay lenses are occasionally found within the Dupi Tila Formation.

Aquifer System Geometry:

The general hydrogeology and aquifer system of the study area are described in Chapter 4. The geometry of the aquifer system was defined using data from over 200 borehole logs, by reference to the elevations of the top and base of different layers. For modelling purposes the complex geological conditions obtained from borehole logs have been approximated by simplified hydrogeological equivalents. The simplified aquifer system consists of four layers: a lower and upper aquifer separated by an aquitard and a semi-confining layer overlying the upper aquifer. This is equivalent to the conceptual model of EPC/MMP as illustrated in Figure 7.2.

The first layer (the upper aquitard) is composed of low permeability clays and silts overlying the upper aquifer. This represents the Madhupur Clay and is present in most of the modelled area. Where the Madhupur Clay is absent, the Bashabo Formation or Floodplain alluvium represents the upper layer. This top layer has no significant horizontal groundwater flow, but acts as a controlling layer with respect to infiltration. The thickness of the first layer is approximately 10 to 15m.

The second layer (the upper aquifer) is mainly composed of fine to medium-fine sands and is found all over the model area at a thickness of 25 to 40m. It represents the upper part of the Dupi Tila Formation.

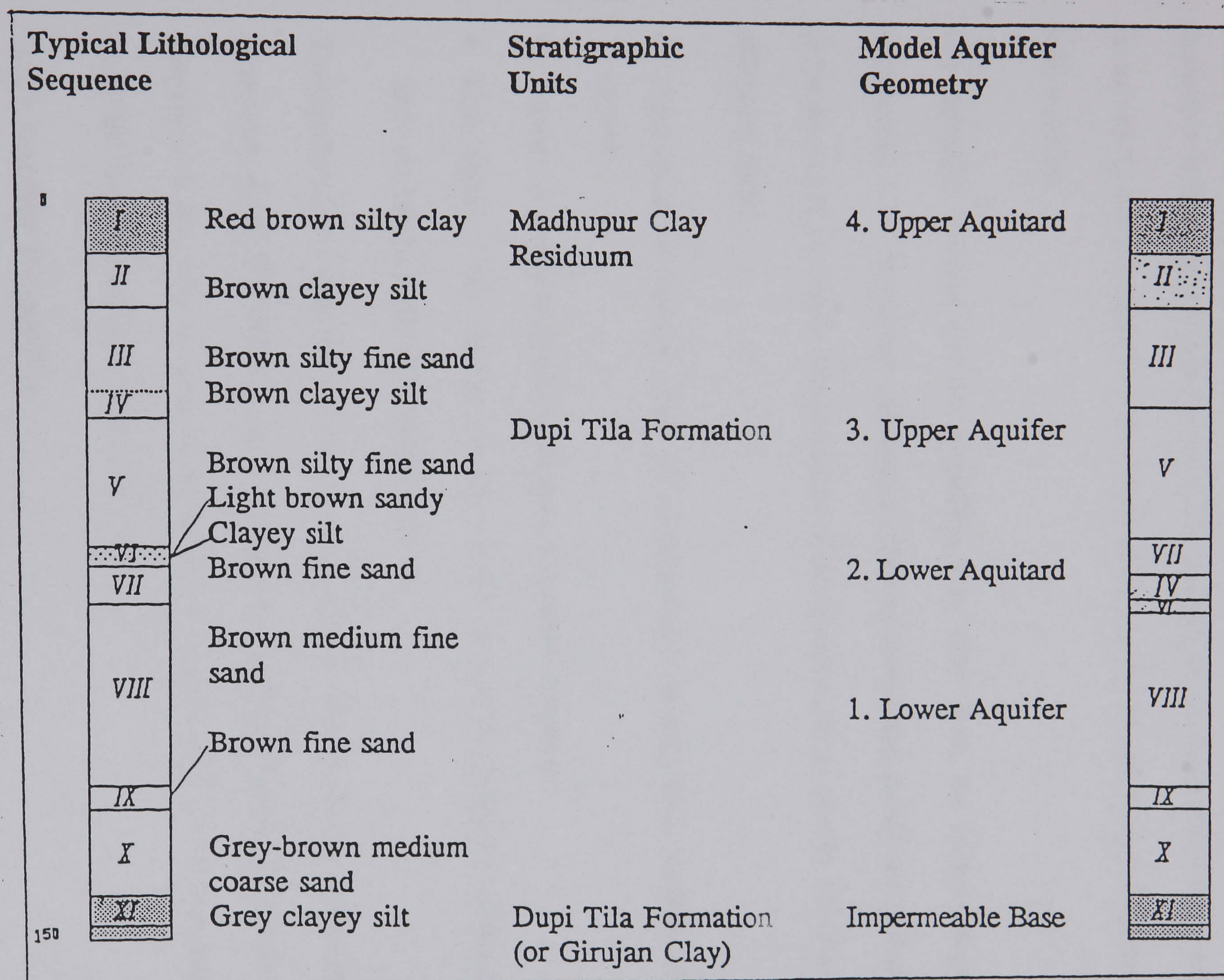


Figure 7.2 Actual and modelled aquifer geometry (after EPC/MMP, 1991)

The third layer (the lower aquitard) separates the lower aquifer from the upper aquifer. The third layer represents the clay lenses within the Dupi Tila Formation. The thickness of this series of clay lenses is highly variable and it is not present in some parts of the modelled area.

The fourth layer (the lower or main aquifer) consists mainly of medium to coarse sands. It represents the deeper levels of the Dupi Tila aquifer, the main aquifer from which water is abstracted by deep tubewells for municipal water supply. The thickness of the main aquifer is 80 to 120m.

The geometry adopted for the modelling was taken from the interpretation of Mott MacDonald, who developed a geological structure model and transferred geometrical data to the model grid network. The procedure of data preparation as used by MMP involved the following steps:

- Digitisation of contour maps of each surface, derived from borehole lithological records.
- Transfer of digitised data to a rectangular network of squares.
- Conversion of the structure model network data to the polygons of the model grid network using a method of weighted means.

The aquifer system geometry of the model developed in this thesis was defined by using the output data of the EPC/MMP geological structure model and checked against borehole data. Elevation of the base of each modelled layer used by EPC/MMP was transferred to SURFER format using the MOD-SURF code.

7.2.3 Aquifer Properties

Concerning aquifer properties, the requirements for groundwater flow modelling include horizontal permeability, vertical permeabilities, and unconfined and confined storage coefficients, for all layers.

The horizontal permeability of both aquifer layers has been inferred from a correlation between the results of pumping tests and lithological profiles (Chapter 4). The horizontal permeability of the upper aquifer ranges from 9 to 18 m/d, whereas the permeability of the lower aquifer ranges from 27 to 35 m/d.

The availability of data on vertical permeability of the four layers is sparse and of limited value. For the aquifers, the vertical permeabilities were derived from the horizontal permebilities by assigning a single value of anistropy (K_h/K_v) for each layer. Anisotropic ratios of 10:1 for both the upper and lower aquifers were adopted, based on the mean anisotropy ratio evaluated by BGS (Barker *et al.*, 1989).

The vertical transfer of water between the surface and the lower aquifer is controlled by the vertical permeability of the upper and lower aquitard. As this is the dominant recharge mechanism over the modelled area and there is very little available knowledge of the vertical permeability, these parameters formed an important variable during model calibration. Uniform values were adopted for both layers initially, and were subsequently refined as calibration proceeded. Additionally, the values for the vertical permeability of the upper aquitard used by EPC/MMP model were modified based on the recent acquisition of information on the geological nature of the surface deposits, particularly the existence of the Bashabo Formation (Chapter 3).

Storativity values for all modelled layers were collated from EPC/MMP model data (EPC/MMP, 1991) and from other published articles (e.g. Miah and Rushton, 1997) and unpublished reports (MMI, 1992). The confined storage coefficients for the upper and lower aquifers were evaluated by taking a mean specific storage and multiplying by the aquifer thickness. A summary of hydraulic parameter values used in the groundwater flow model calibration is given in Table 7.3.

7.2.4 Piezometry

The piezometry for the Dupi Tila aquifer used for calibration was based on measurements in nine observation boreholes in the modelled area. The location of observation wells is shown in Figure 7.3. There are no geo-referenced locations for any of these observation wells, and in some cases, it is suspected that the locations given in the BWDB data may not be accurate. Weekly water level data were collected for the observation wells with respect to the Public Works Datum (PWD) level. Some of these boreholes have long monitoring records, from 20 to 30 years duration. However, since 1986, monitoring data is available only for the upper aquifer. There is no monitoring of water levels in the upper aquitard and in the lower aquifer. Average piezometric levels were used to define the flow pattern. Contours of piezometric heads were also plotted for high and low water level conditions to consider regional flow and to infer boundary conditions. The observed sequential piezometry of the Dhaka Dupi Tila aquifer as it is developed over the 30 years from 1966 to 1996 is shown in Figure 7.4. The quality of the data is reasonable, although missing data are a problem for some of the wells.

7.2.5 Recharge

The potential recharge values determined by the MPO (MPO, 1991) for Bangladesh form the basis for the calculation of natural recharge. For Dhaka city, the potential recharge was modified by EPC/MMP (EPC/MMP, 1991) to account for the following:

- The reduction in infiltration capacity of the ground surface due to paved and built-up areas
- The existence of storm water drainage systems which reduce the occurrence of surface flooding for extended periods of time
- Flood protection schemes which reduce the flood depth.

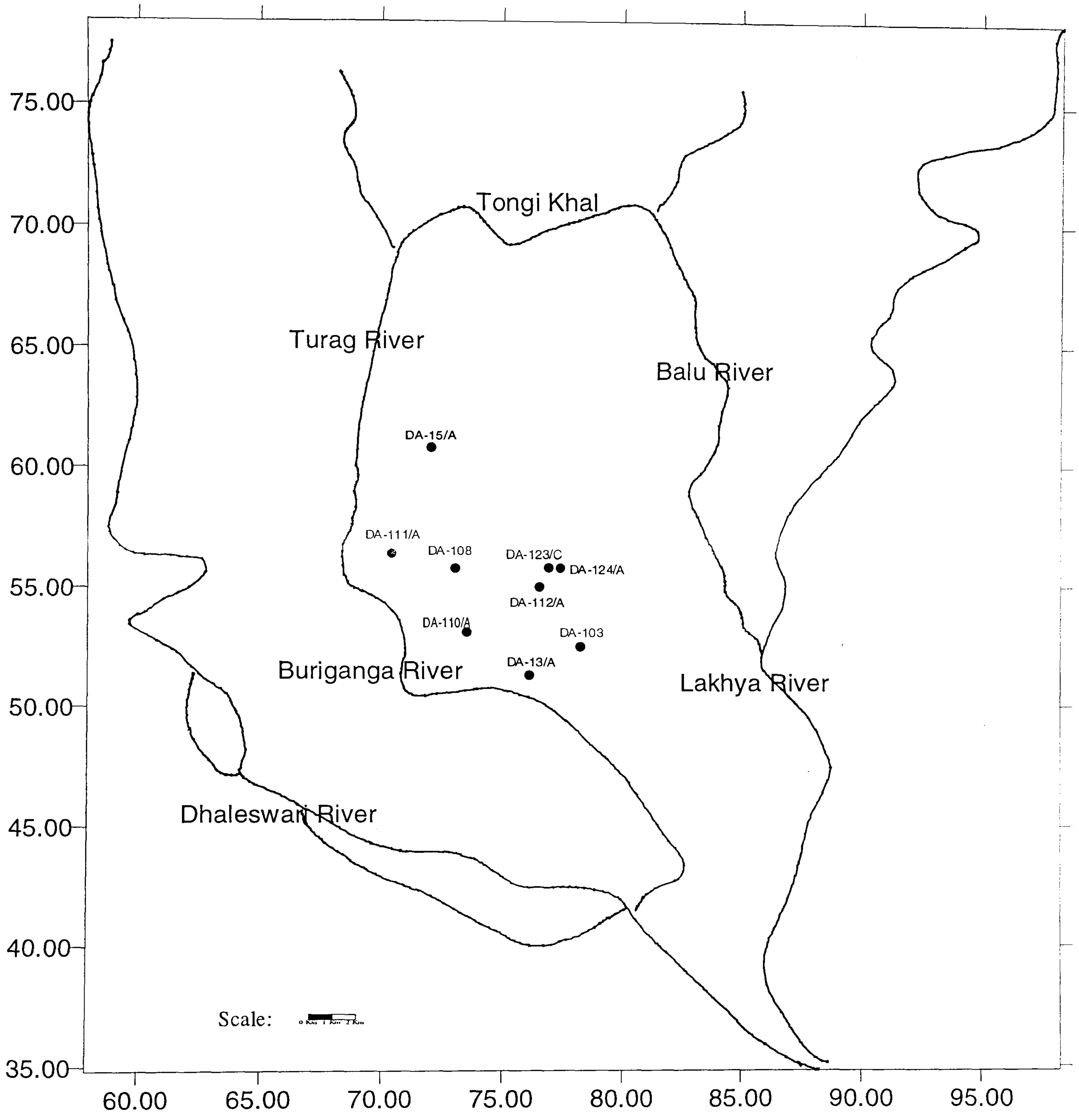


Figure 7.3 Location of BWDB water level observation wells in Dhaka city

The range of potential recharge rates, modified in the way by EPC/MMP varies from 0.09 to 1.25 mm/d.

Although paving and construction in Dhaka urban area is expected to cause a reduction in natural recharge, an important additional recharge component is the return flow from water supply and urban drainage. In the EPC/MMP (1991) methodology, the return flows have been incorporated as a distinct additional source of recharge, calculated as a proportion of total abstraction for water supply and industrial use, and based on comparison with other urban areas. This proportion ranges from 25% to 45% of the total abstraction.

Although in Dhaka a reduction of recharge due to urbanization might be expected the incorporation of return flows actually increases the amount of recharge available to the aquifer.

However, actual rates of recharge are strongly controlled by the surface geology, being limited by the infiltration capacity of the surface material. The range of vertical permeability for the Madhupur Clay is 10^{-2} to 10^{-4} m/d (Section 4.3.1). Therefore the range of actual recharge is more realistically taken as 0.09 mm/d to 1.0 mm/d.

Under the "aquifer full" condition appropriate for the start of the modelled period, 0.09 mm/d has been taken as recharge uniformly throughout the region. For the transient model, therefore, to incorporate the effect of increased abstraction with time, recharge is uniformly increased from 0.09 mm/d to 1.0 mm/d over the simulation period, to account for the rising proportion of return flow that contributes recharge (Section 7.2.6). Moreover, due to intensive abstraction the vertical gradient in the aquifer increases the infiltration capacity in the clay. This basis for the recharge assessment is justified to an extent by the successful calibration achieved by in the initial study by EPC/MMP (EPC/MMP, 1991), and in the modified MODFLOW model described here.

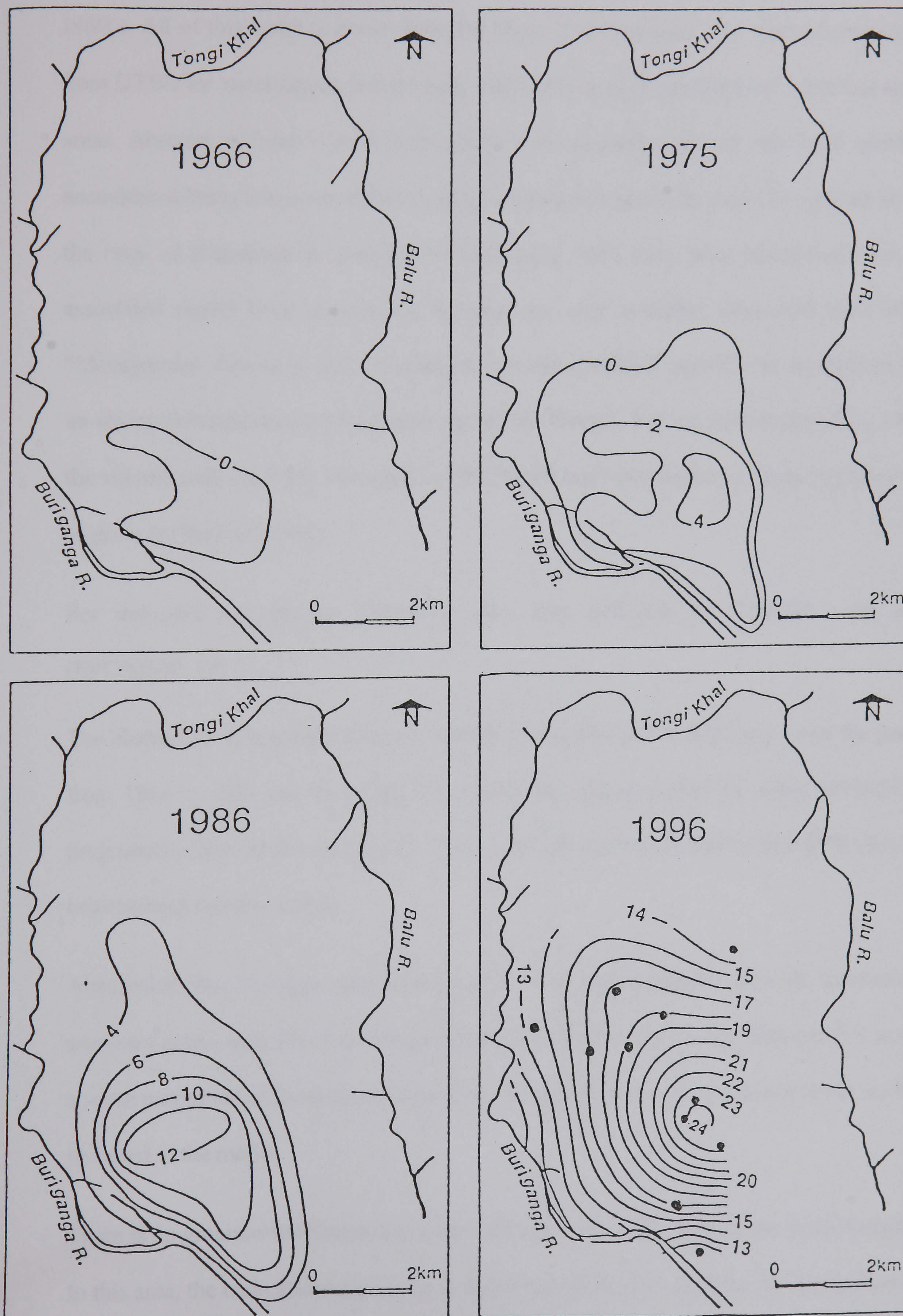


Figure 7.4 *Sequential piezometry of the Dupi Tila aquifer, 1966-1996 (as water level below PWD datum, in meters).*

7.2.6 Abstraction

The annual abstraction of groundwater by DWASA has risen continuously since the early 1960's. All of this water is drawn from the Dupi Tila Formation. The rates of abstraction from DTWs for water supply and for industrial use have been specified for individual small areas. Abstraction from WASA wells can not be accurately defined; the main problem encountered being that none of the tubewells are properly geo-referenced. For private wells, the rates of abstraction as specified for individual wells have been distributed over the associated model area. Abstraction histories are only available from mid-1983 when "Management, Operation and Distribution Services (MODS)" zones were established and an abstraction-monitoring programme started by WASA. For the period preceding 1983, the volume abstracted was estimated by EPC/MMP from the number of operating tubewells as given by Parsons (1980).

For industrial and private abstraction data, data collected by DWASA were used (EPC/MMP, 1991).

The abstraction data collected for the DWASA model by EPC/MMP only cover the period from 1964 to 1989 and these data were processed and converted by using MOD-SURF programme. Data for the period after 1989 were collected by the author from DWASA and incorporated into the model.

Abstraction from the upper part of the aquifer is by hand-pumped tubewells, estimated to represent at less than 5% of the total abstraction from the main aquifer. Because this is such a small proportion of the total and the details of the abstraction are unknown, it has not been included in the model.

There is no groundwater abstraction from the Dupi Tila aquifer beyond the river Buriganga. In this area, the main abstraction is from the Holocene alluvial aquifers. No abstraction data is available beyond the river Buriganga for the Dupi Tila aquifer.

7.3 Groundwater Flow Modelling

7.3.1 Model Software

MODFLOWwin32 was used to model the Dhaka aquifer system. MODFLOW is a modular, three-dimensional, finite difference groundwater flow model (McDonald and Harbaugh, 1988) developed by the United States Geological Survey (USGS). The modular structure of the package allows very flexible yet efficient modelling of the important aspects of the groundwater system. MODFLOW uses a block-centred, technique to simulate both horizontal and vertical flow of groundwater for steady state and transient conditions. The version MODFLOW win32 used for this study runs within the Windows operating system and is a 32-bit programme untilizing all available memory. To speed data input and processing of results, the models were run through a pre - and post-processor package Groundwater Vistas (GV).

MODFLOW is well-known modelling software, which is widely used and has been verified for an extensive range of different conditions. In particular, for this thesis, MODFLOW has been selected since it provides an easy link to the solute transport modelling software MT3D.

Groundwater Vistas (ESL, 1998) provides a user-friendly environment to run MODFLOW packages. It provides a graphical interface which greatly simplifies the data input to these sophisticated models. It can display the results in a variety of ways, including contouring in plan and section, velocity vectors and mass balance analyses.

7.3.2 Development of the Model

Conceptual Model

The four-layer model developed by the EPC/MMP (EPC/MMP, 1991) has been retained for this research. However, direct input of the EPC/MMP data to MODFLOW created a serious problem with overlapping layers. The 'grid math' options under the SURFER programme were used to solve this problem. The model layers and their geological and hydrogeological equivalents, and the MODFLOW layer type are given in Table 7.1.

Table 7.1 *Modelled layers and their geological and hydrogeological equivalent*

Model layer	Geological unit	Hydrogeological unit	MODFLOW layer type
1	Madhupur Clay	Upper aquitard	1 (Unconfined top layer)
2	Dupi Tila	Upper aquifer	3 (Confined/Unconfined, variable T)
3	Dupi Tila	Lower aquitard	3 (Confined/Unconfined, variable T)
4	Dupi Tila	Lower aquifer	3 (Confined/Unconfined, variable T)

The four-layer model has been retained using different aquifer parameters, to represent the different geological and hydrogeological conditions of the region beyond the river Buriganga.

Model domain, Grid and Boundaries

The model covers an area of approximately 600 km^2. The grid of the model was based on a network of 30 rows and 40 columns, generating a mesh of squares with resolution of 500*500m. The model grid network and boundaries are shown in Figure 7.5.

Dhaka city is surrounded by the rivers Buriganga, Turag, Tongi and Balu on almost all

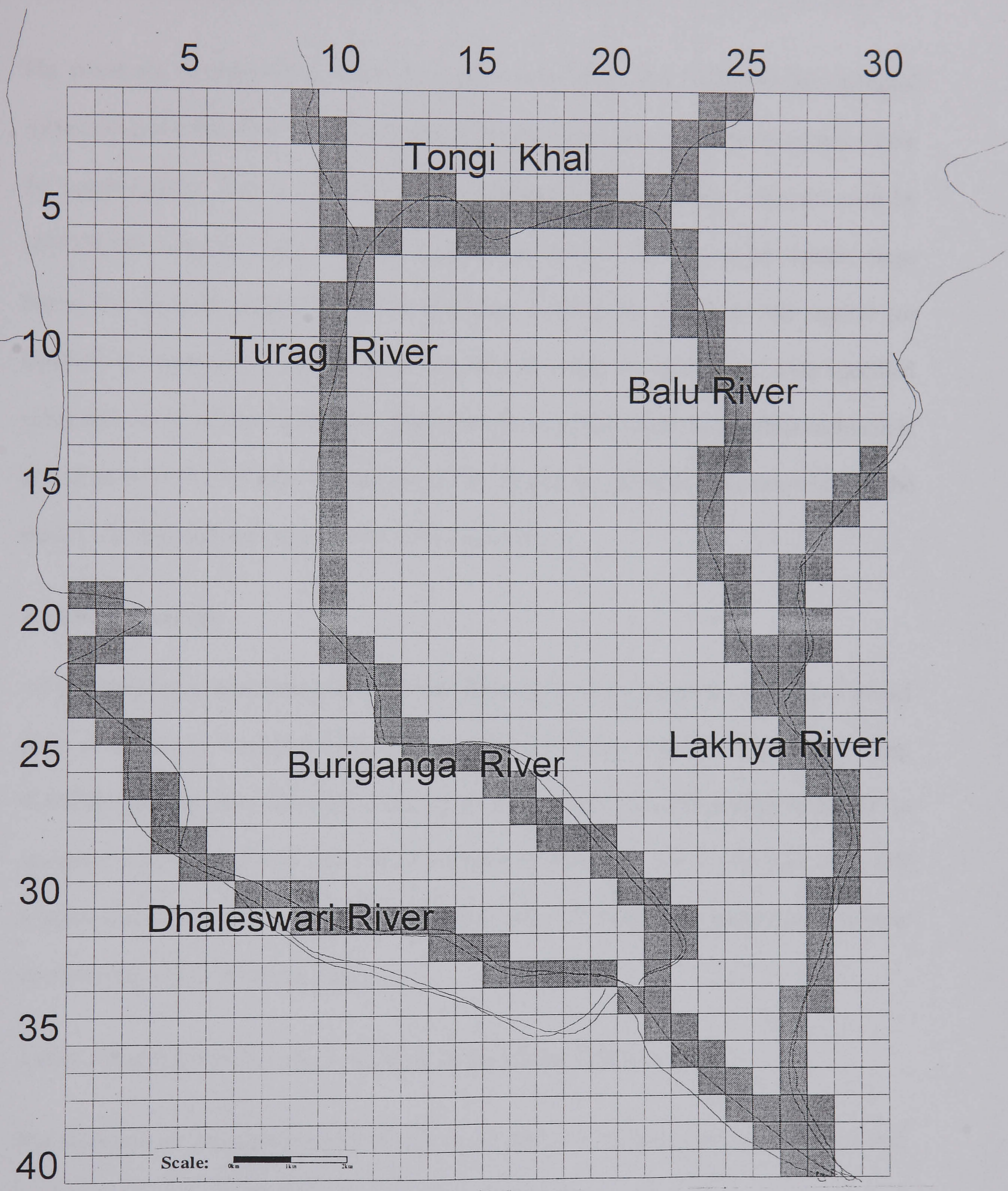


Figure 7.5 Model grid network and boundaries

sides and in parts the rivers actually define the city limit. Therefore to the west, south and east the model area has been extended out beyond these rivers to the more distant rivers, the Dhaleswari and Lakhya. The Tongi Khal remains as the northern boundary of the model.

The rivers are represented as 'River Boundary' conditions within MODFLOW, included within the grid cells, which effectively model the rivers as a specified head boundary within the upper aquifer. This is a special type of head-dependent boundary condition used by MODFLOW whereby flow out of the river cell is limited if the head in the aquifer drops below the riverbed (Figure 7.6). The exchange between the river and the aquifer (or aquitard) is computed as vertical flow. Riverbed elevation and river stage were specified using data monitored by the BWDB. The hydraulic conductivity of the riverbed sediment is estimated to be 1 m/d with a thickness of 1m. Sensitivity analysis demonstrated that the model is moderately insensitive to these two parameters.

Aquifer Properties

Aquifer properties were arranged by the formation of "zones" consisting of blocks of model grids or blocks of modelled cells with common parameter values, computed by using SURFER gridded files. "Zoning" is one of the fundamental concepts employed by GV in assigning aquifer properties and some boundary conditions to the model grid cells. GV requires that each model parameter be defined in terms of zones. Each parameter may have its own zone pattern and zone values.

Values of some parameters were adjusted during model calibration.

The thickness of the aquifer layers was initially based on averages derived from borehole log data, as given in Table 7.2:

The thickness of the model layers along the row 20 is given as an example in Figure 7.7.

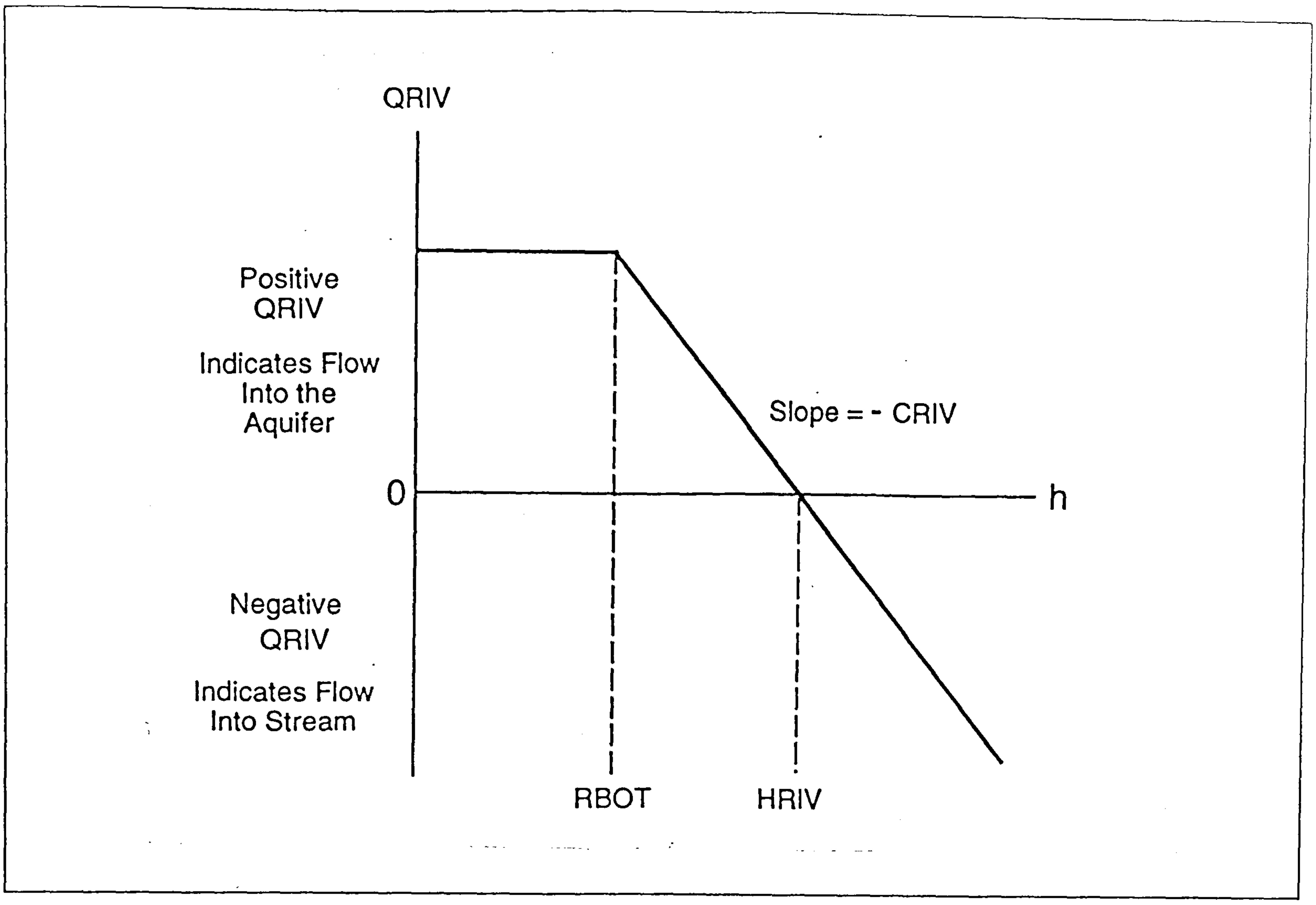
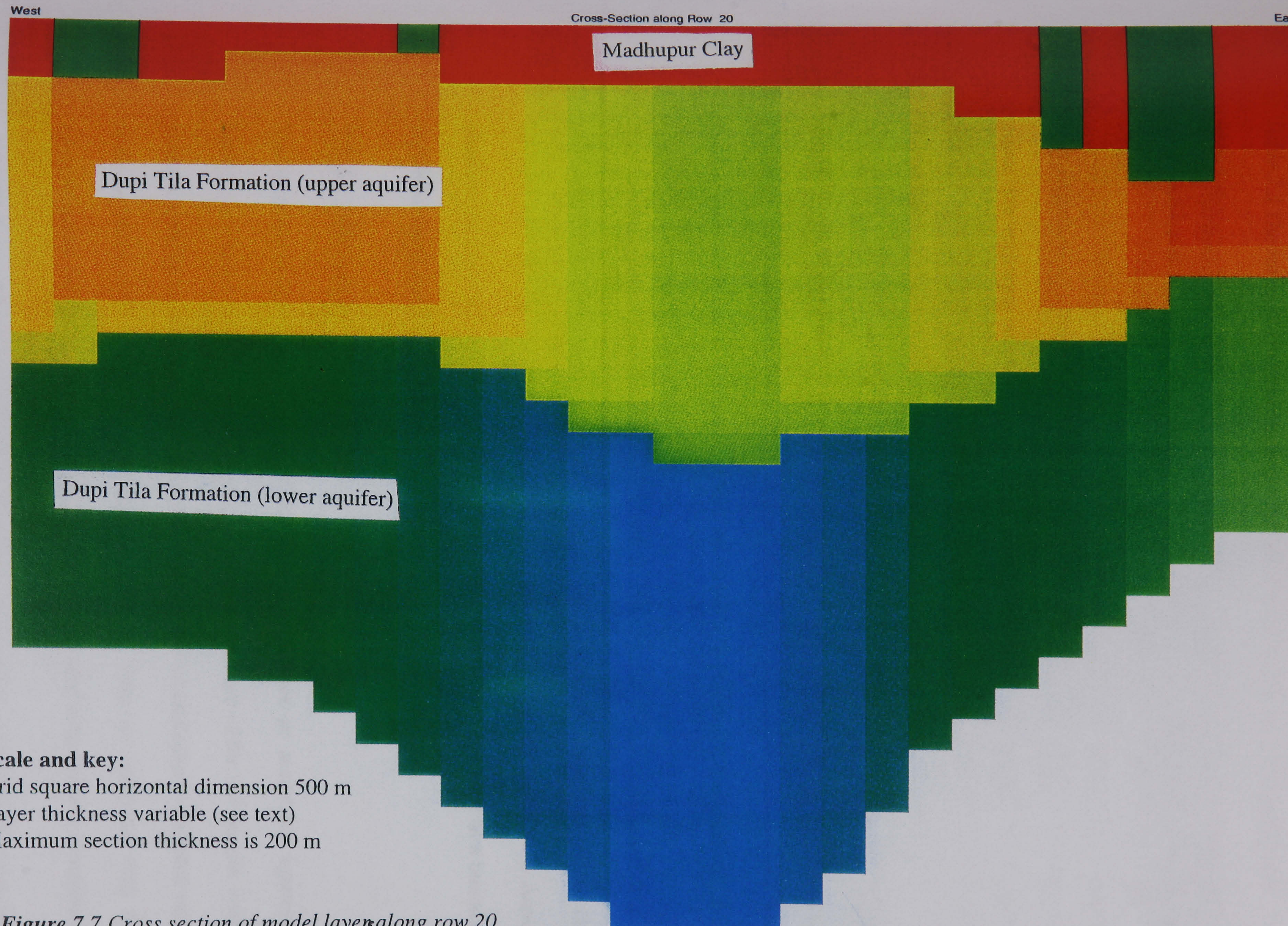


Figure 7.6 River- aquifer interaction (Plot of flow (QRIV), from a stream into a cell as a function of head (h) in the cell where RBOT is the elevation of the bottom of the streambed and HRIV is the head in the stream (after Kresic, 1997).

Table 7.2 Model layer and average thickness

Hydrogeology Unit	**Model Layer**	**Average Thickness (m)**
Upper aquitard	1	10-15
Upper aquifer	2	30-40
Lower aquitard	3	5
Lower aquifer	4	80-120

The hydrogeological parameters specified in the model are given in a tabular form below (Table 7.3).



Scale and key:
Grid square horizontal dimension 500 m
Layer thickness variable (see text)
Maximum section thickness is 200 m

***Figure** 7.7 Cross section of model layers along row 20*

Table 7.3 The range of Hydrogeological parameter values adopted during calibration

Layer	Horizontal Permeability (K_H) m/d	Vertical Permeability (K_v) m/d	Specific Yield, Sy	Confined Storage, S	Effective Porosity, ne
1	0.005 and 0.05	0.005 and 0.05	0.0025	0.0001	10%
2	9-18	0.9-1.8	0.10	0.0002	15%
3	0.02	0.02	0.020	0.0001	15%
4	27-35	2.7-3.5	0.15	0.0005	15%

Recharge

A constant recharge rate of 0.09mm/d was initially applied to the top model layer across the whole model domain. For the transient model, a time variant recharge was applied increasing from 0.09mm/d to 1.0 mm/d over the period of simulation.

Abstraction

The "well package" under MODFLOW is designed to simulate inflow or outflow through recharging or pumping wells. Wells are handled in the package by specifying the location of each well and its abstraction rate Q for each stress period of the simulation. Annual abstractions for every well within each grid square were summed and used as a boundary condition input parameter for the model.

7.3.3 Calibration

The purpose of groundwater model calibration is to achieve an acceptable agreement between modelled response and the equivalent known response of the real aquifer system (measured data) by adjusting input parameters. During model calibration, simulated values such as piezometric heads and groundwater discharge rates are compared with field measurements. Not all parameters associated with the simulated water balance components of the Dhaka model are well defined for the whole model region. A number of uncertainties arise through lack of data, its imprecision and extrapolation. The effectiveness of the calibration is strongly determined by the availability and quantity of the data, both for input to the model and for comparison with the simulations. During the model calibration, the most important adjustment was to increase the vertical conductivity of the top layer and reduce the recharge rate to make a good adjustment between modelled and observed piezometry.

The model calibration generally consists of two stages. The first stage is a steady state calibration, in which stable, time-independent conditions are simulated using the model and compared with conditions in the real system under constant inflow/outflow conditions. The second stage is a transient calibration where the model's response to a historical record of recharge and abstraction data is tested against the observed response of the aquifer system. To quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of model parameters, a sensitivity analysis was carried out to test the effects of changes in parameter values by a factor of two on the simulated head distribution (Table 7.4). The analysis shows the predicted heads are most sensitive to the recharge rate, followed by the hydraulic conductivity of the top layer.

Steady State Calibration

In the modelling context, steady state conditions exist when inflow to the aquifer system is in equilibrium with outflow from the system and no internal storage changes are occurring. Due to the large-scale and continuously increasing abstraction of groundwater in Dhaka city, such conditions have not existed within the last 25-35 years (EPC/MMP, 1991). The earliest water level observations for Dhaka city were made in 1966 (Welsh, 1970). By extrapolating back to 1964, steady state water level conditions have been derived. During the steady state calibration process, adjustments were required to the values of the vertical

Table 7.4 Sensitivity of model parameters

Parameters	Lower Value	Upper Value	Effect
Hydraulic conductivity of upper aquitard	0.0001	0.10	Major
Recharge	0.009 mm/d	1.25 mm/d	Major
River bed conductivity	0.1 m/day	2 m/d	Minor
Hydraulic conductivity of the upper aquifer	9 m/day	18 m/d	Moderate
Hydraulic conductivity of the lower aquifer	20 m/d	35 m/d	Major
Storage coefficient of the upper aquifer	0.00001	0.05	Moderate
Storage coefficient of the lower aquifer	0.0001	0.0008	Moderate

permeability of the top layer, and to recharge values. This initial steady state simulation was used for the following purposes:

- Verification of model parameters derived from previous studies
- Generation of a head distribution suitable for using as the starting heads for the subsequent transient calibration.

The results of the steady state calibration, for the upper aquifer layer, are shown in Figure 7.8.

Transient Calibration

The model was calibrated under transient conditions over the period of time for which historical records of water levels and abstraction are available (1965-1997). The essential requirements for the transient calibration are therefore reliable records over a sufficiently long period of time of groundwater abstractions, water levels in a network of monitoring wells, and factors which may influence recharge. The initial heads used for the transient calibration were derived from the steady state simulation. A time step of one year was used; 35 time steps represent the period of 1964-1998.

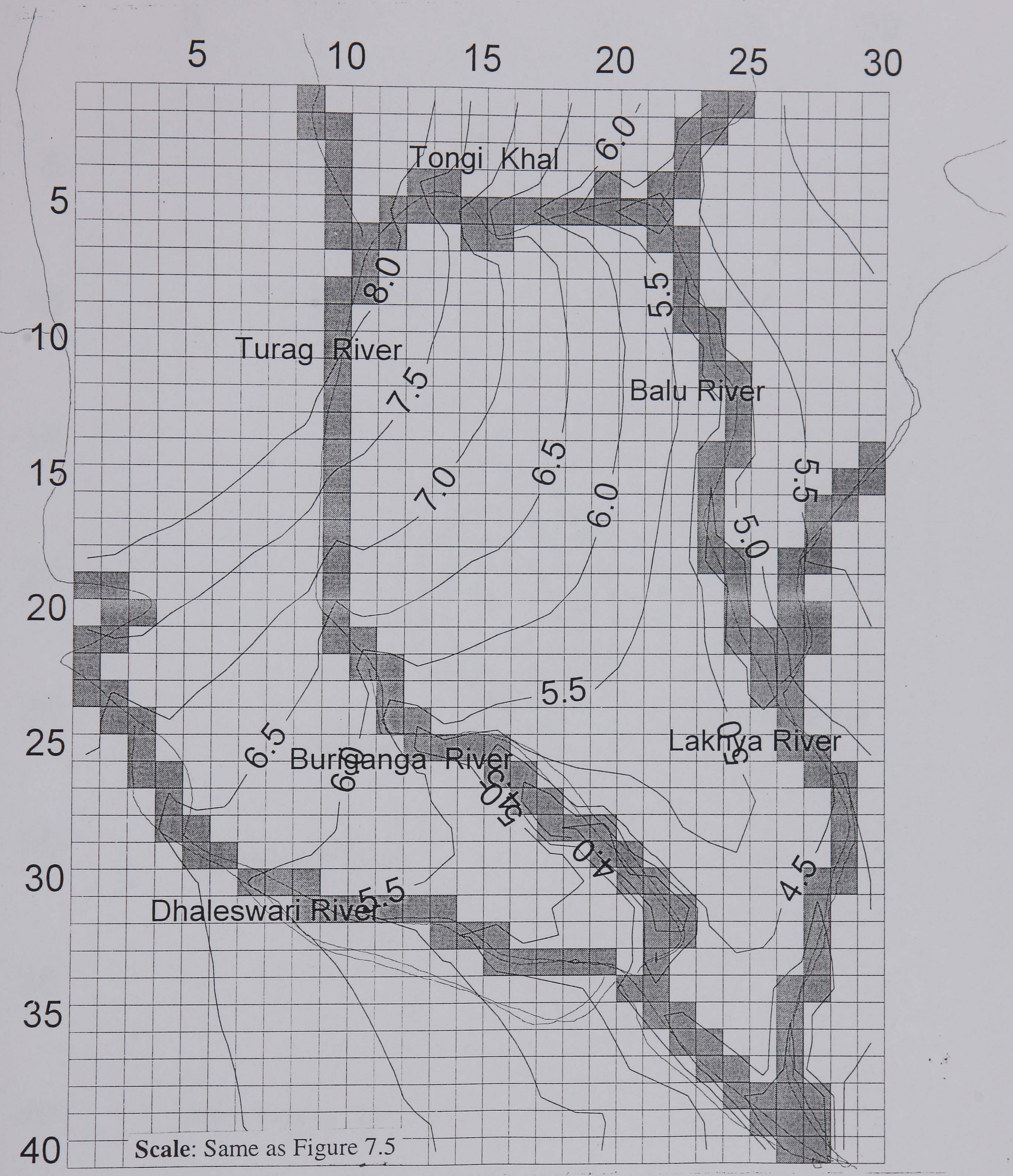


Figure 7.8 Results of the steady state simulation in the Dupi Tila aquifer

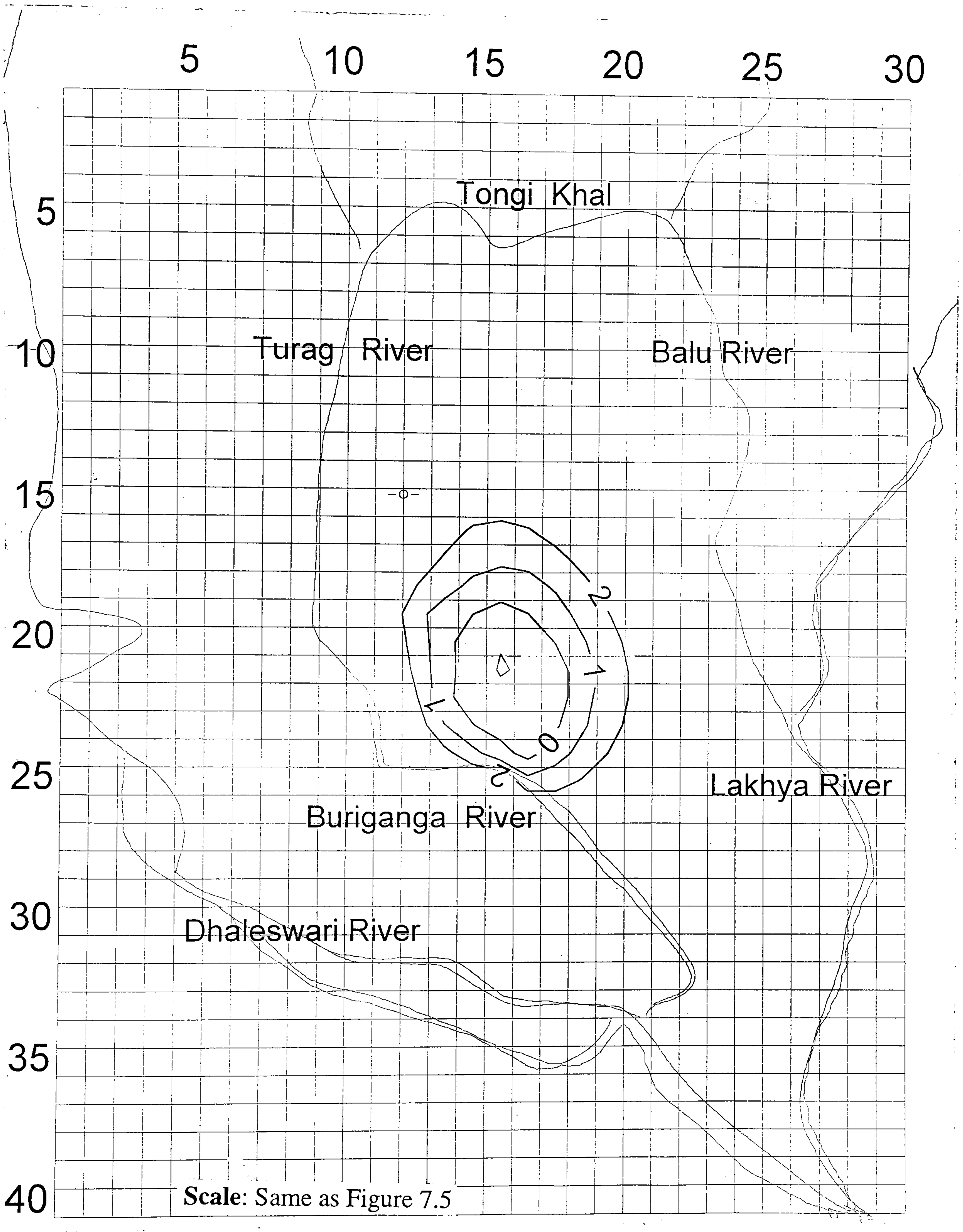


Figure 7.9 *Calibrated piezometry (contour in metre) of the upper aquifer for the year 1966*

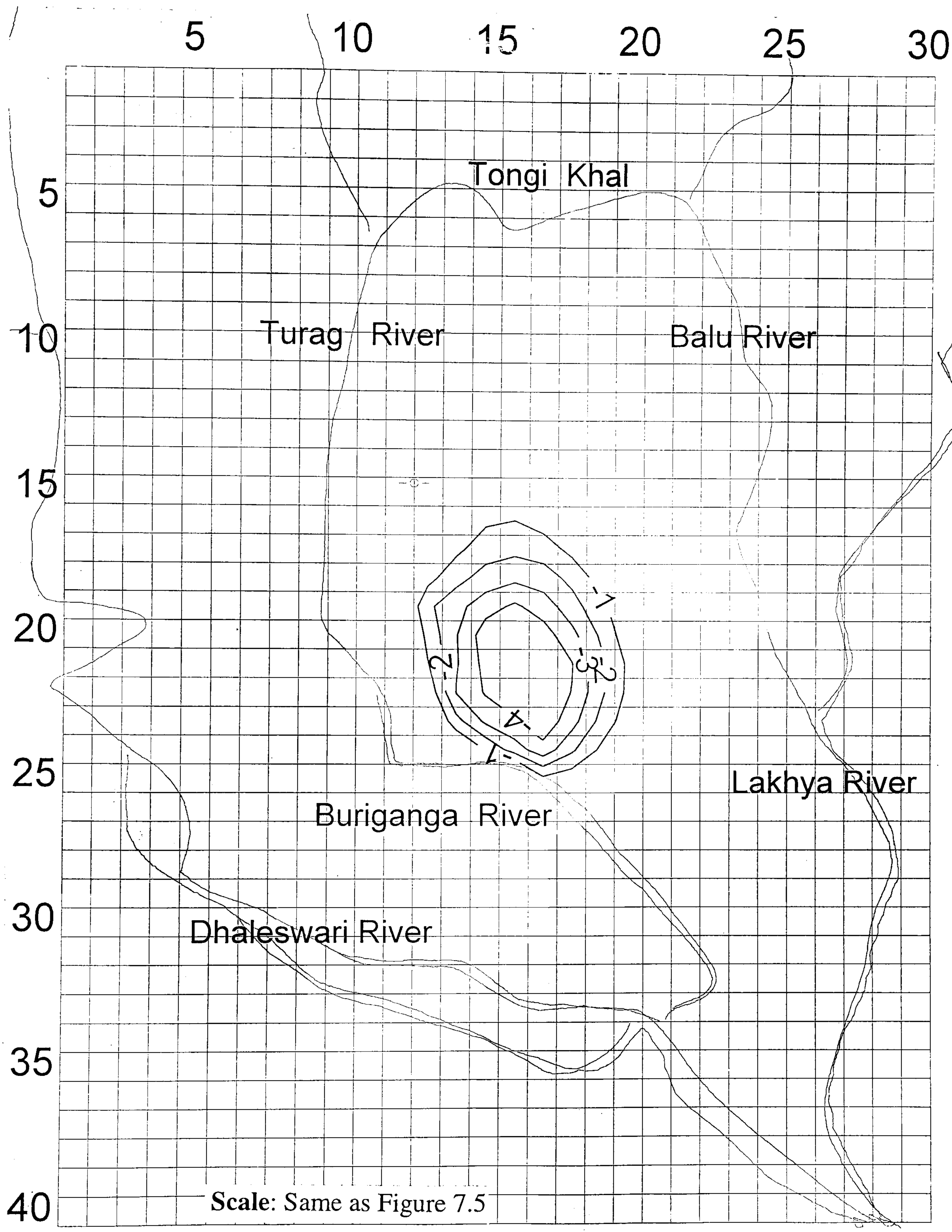


Figure 7.10 Calibrated piezometry (contour in metre) of the upper aquifer for the year 1975

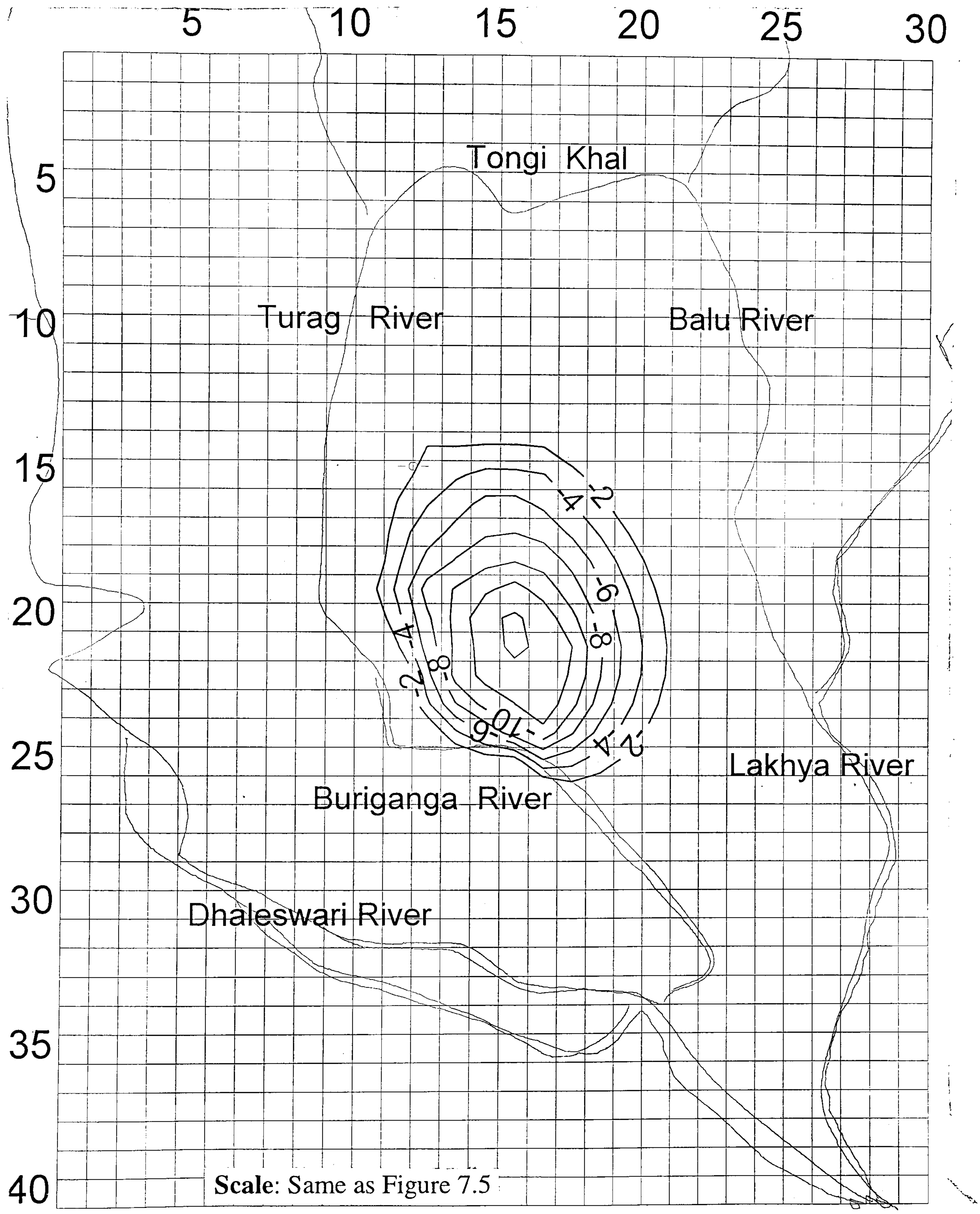


Figure 7.11 Calibrated piezometry (contour in metre) of the upper aquifer for the year 1986

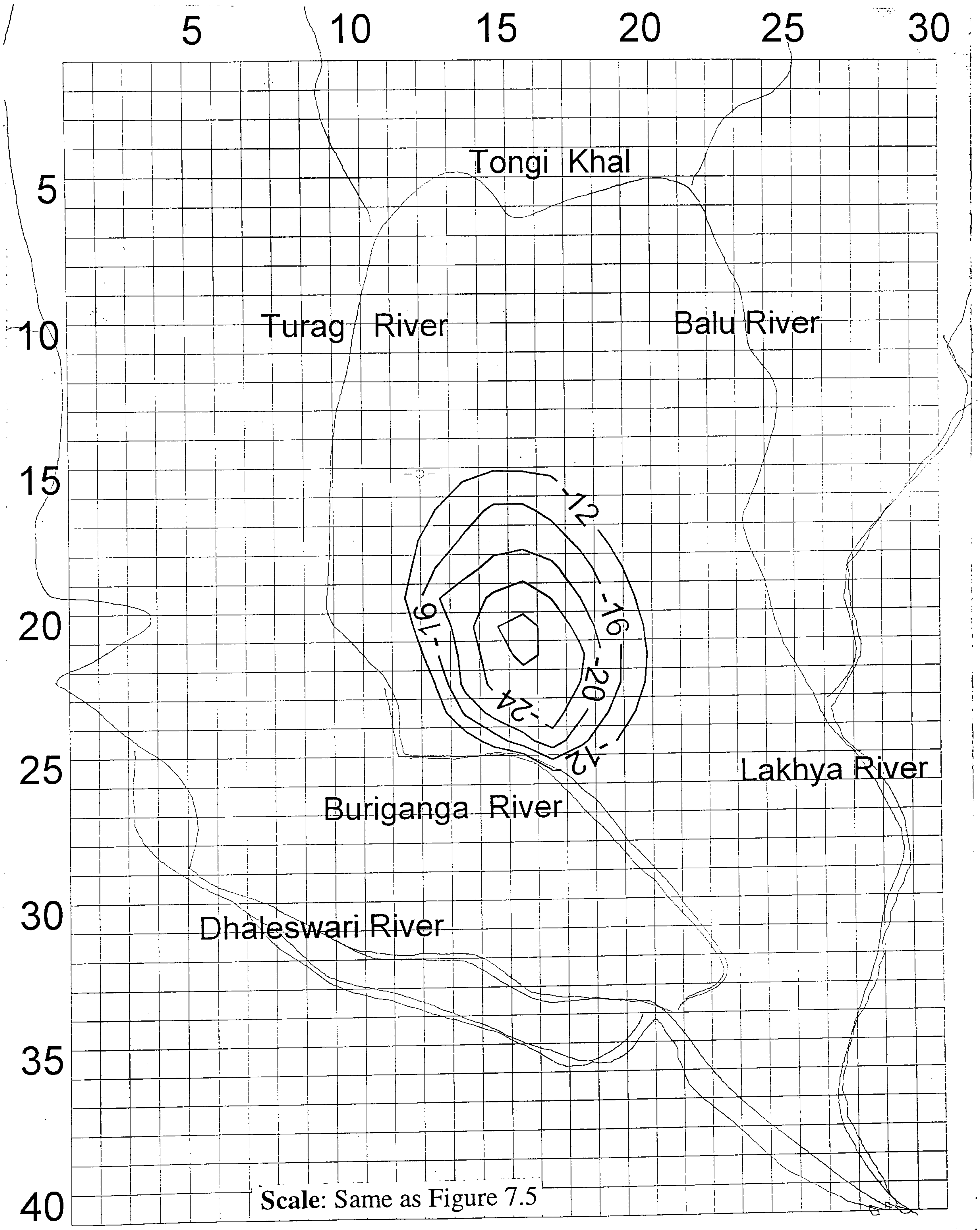
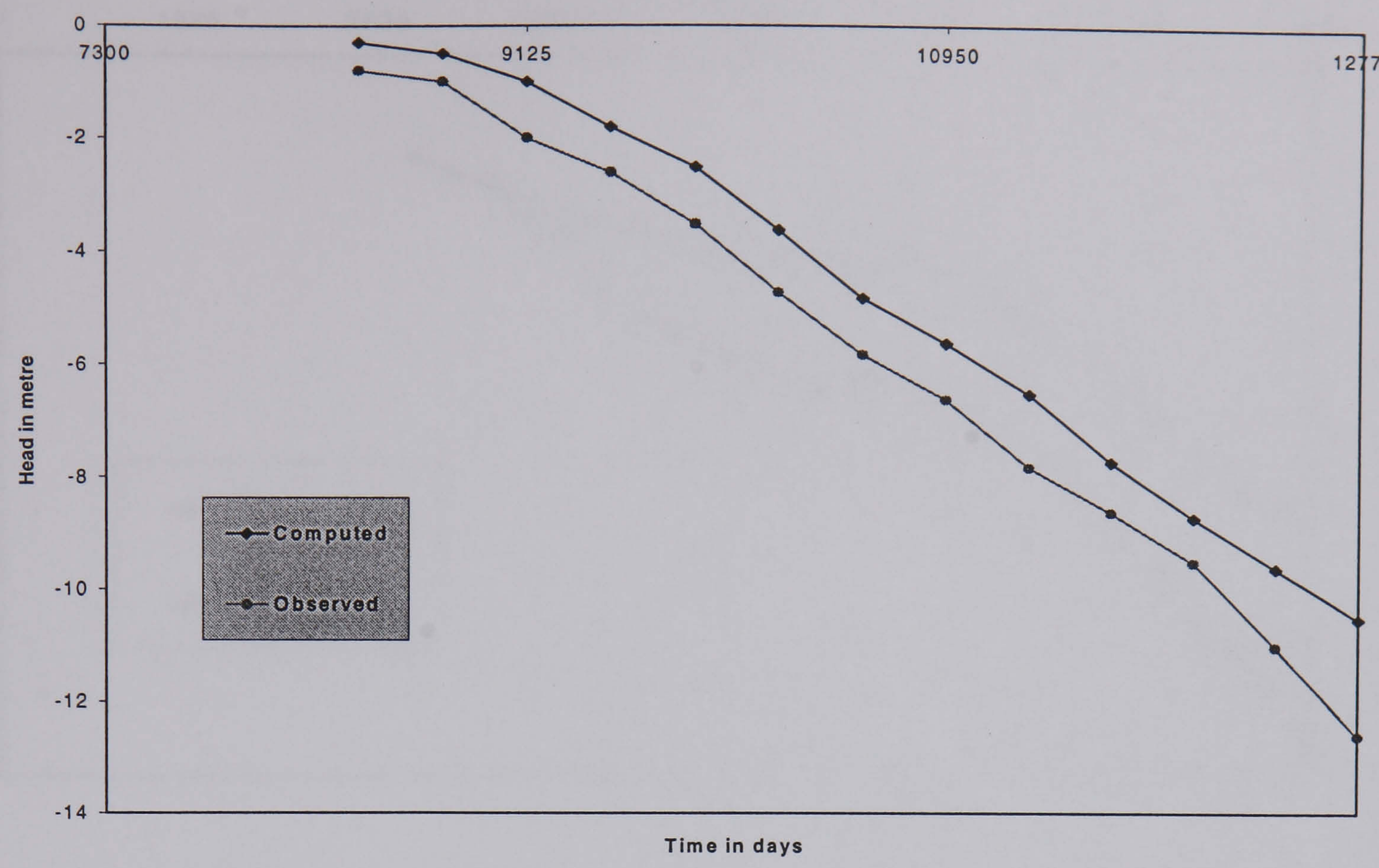


Figure 7.12 Calibrated piezometry of the upper aquifer for the year 1996



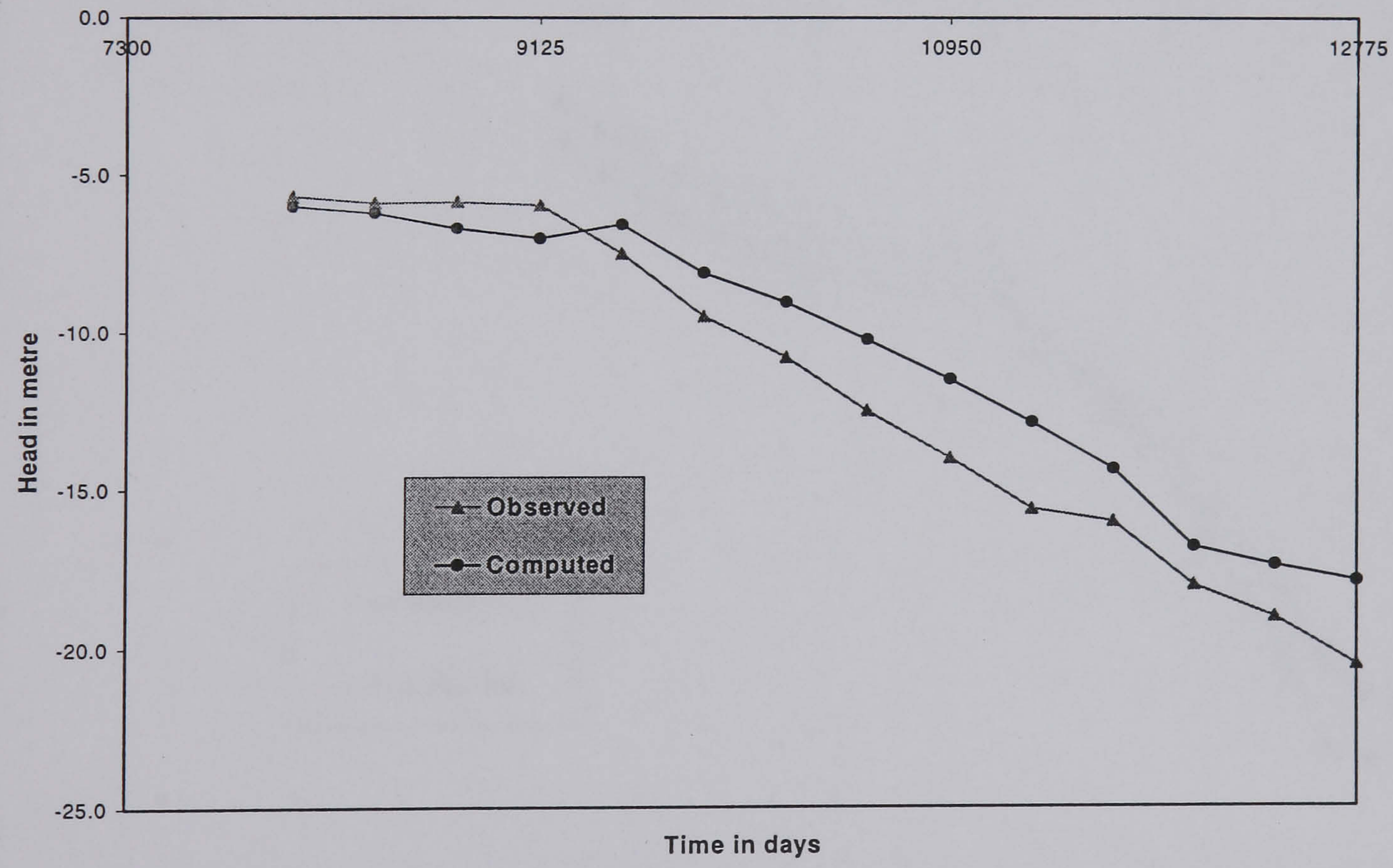
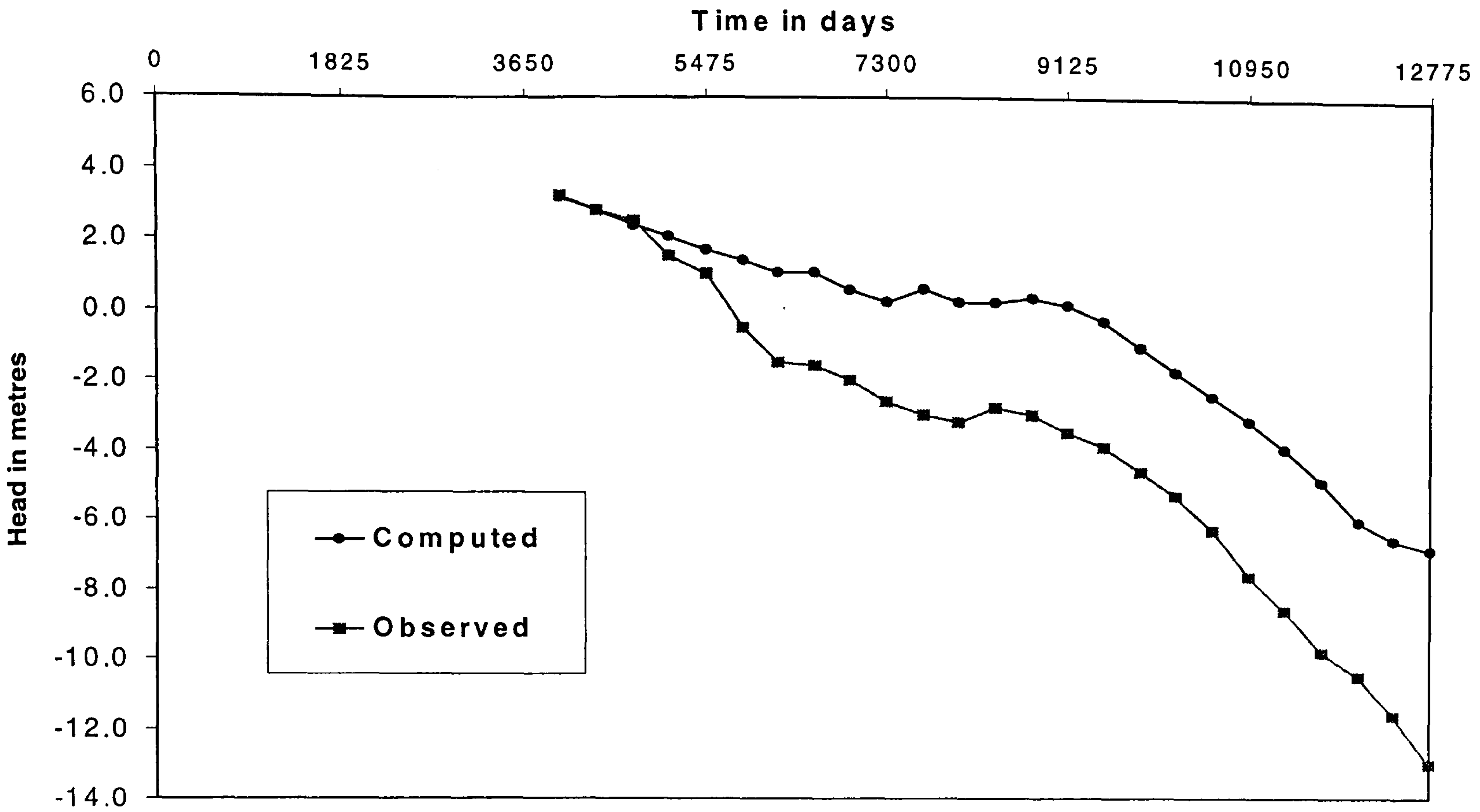


Figure 7.13 *Calibrated and observed hydrograph for the upper aquifer, DA-15/A (top) and DA-103 (bottom)*



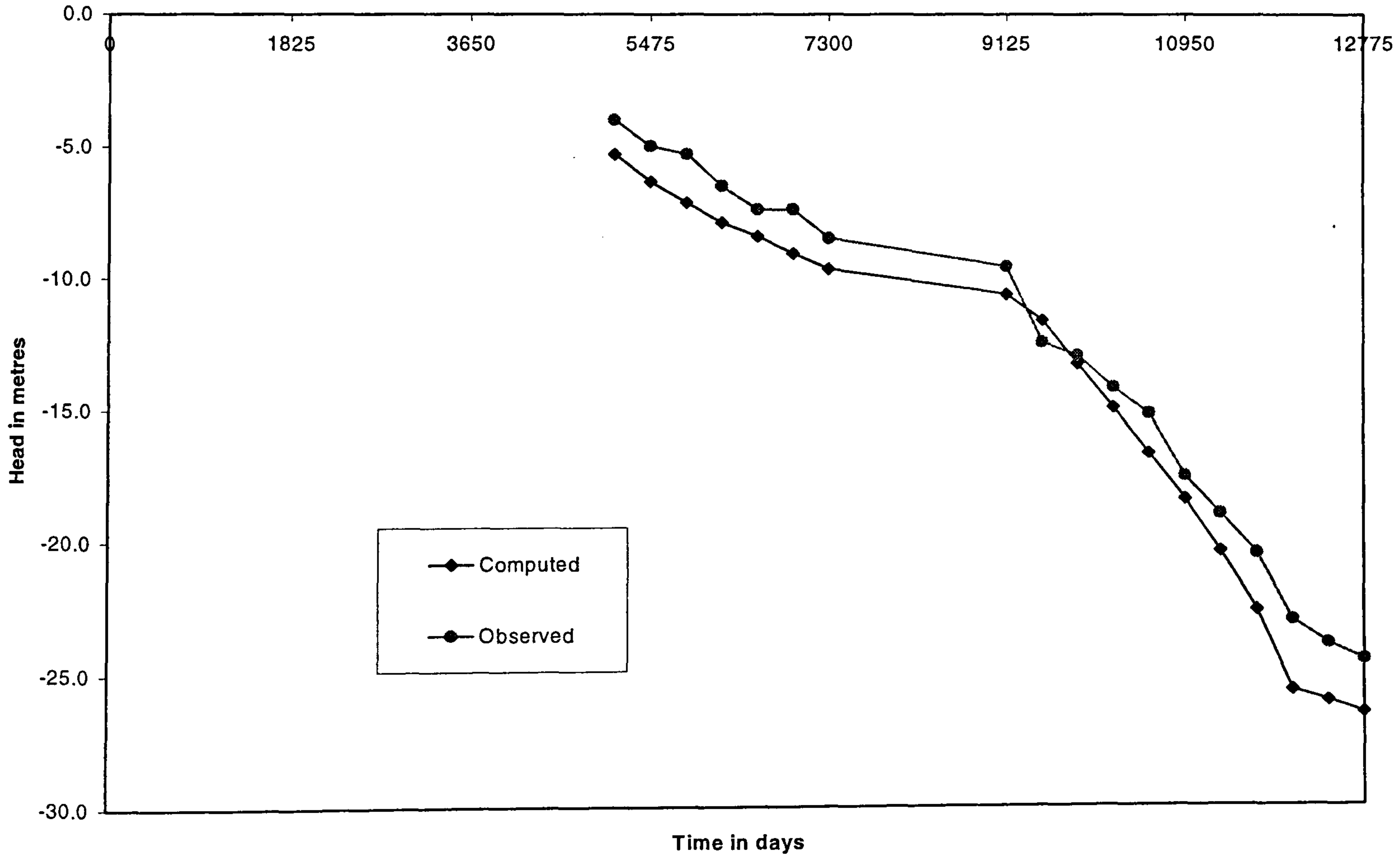
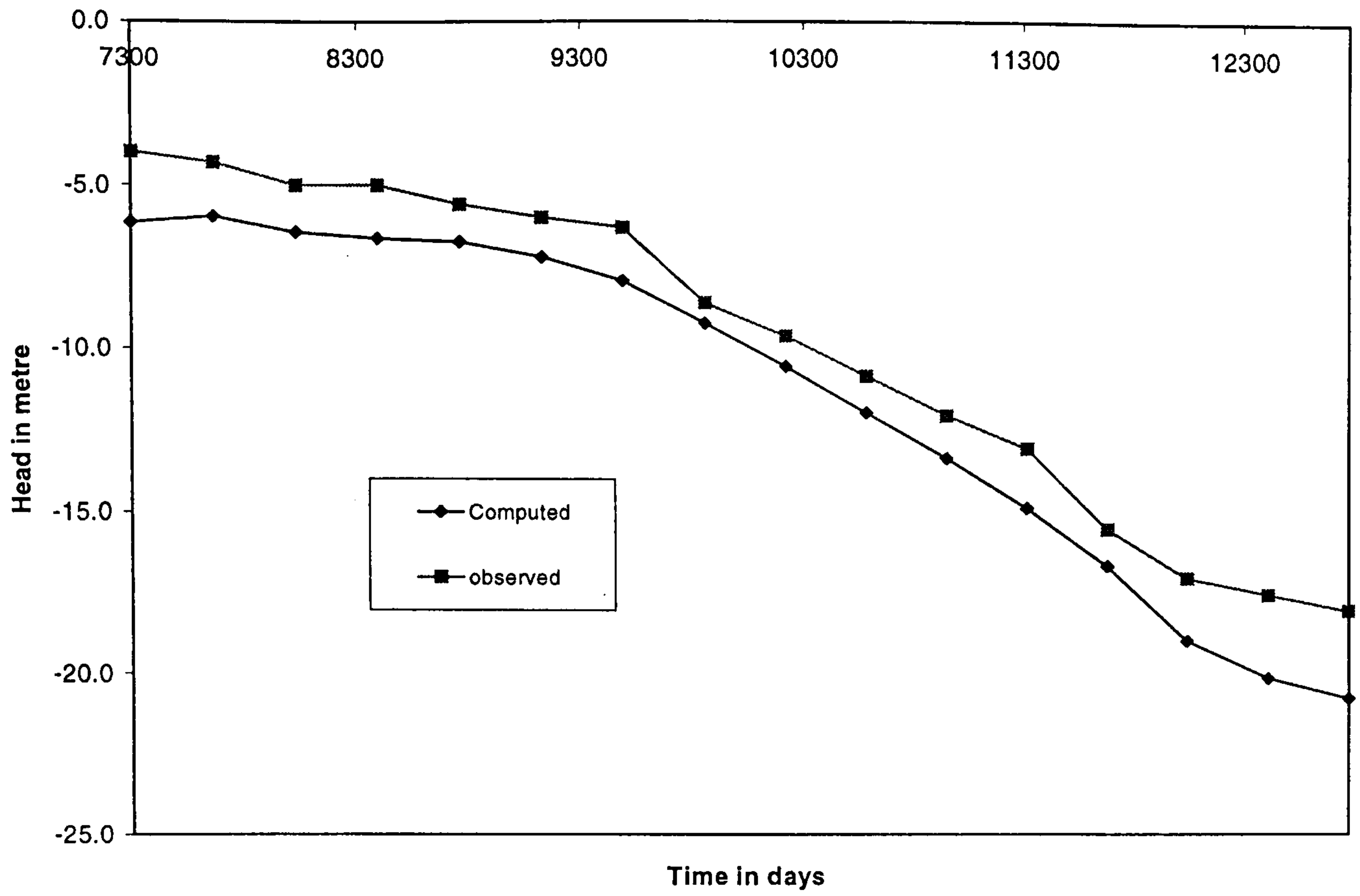


Figure 7.14 *Calibrated and observed hydrograph for the upper aquifer, DA-111/A (top) and DA-112/A (bottom)*



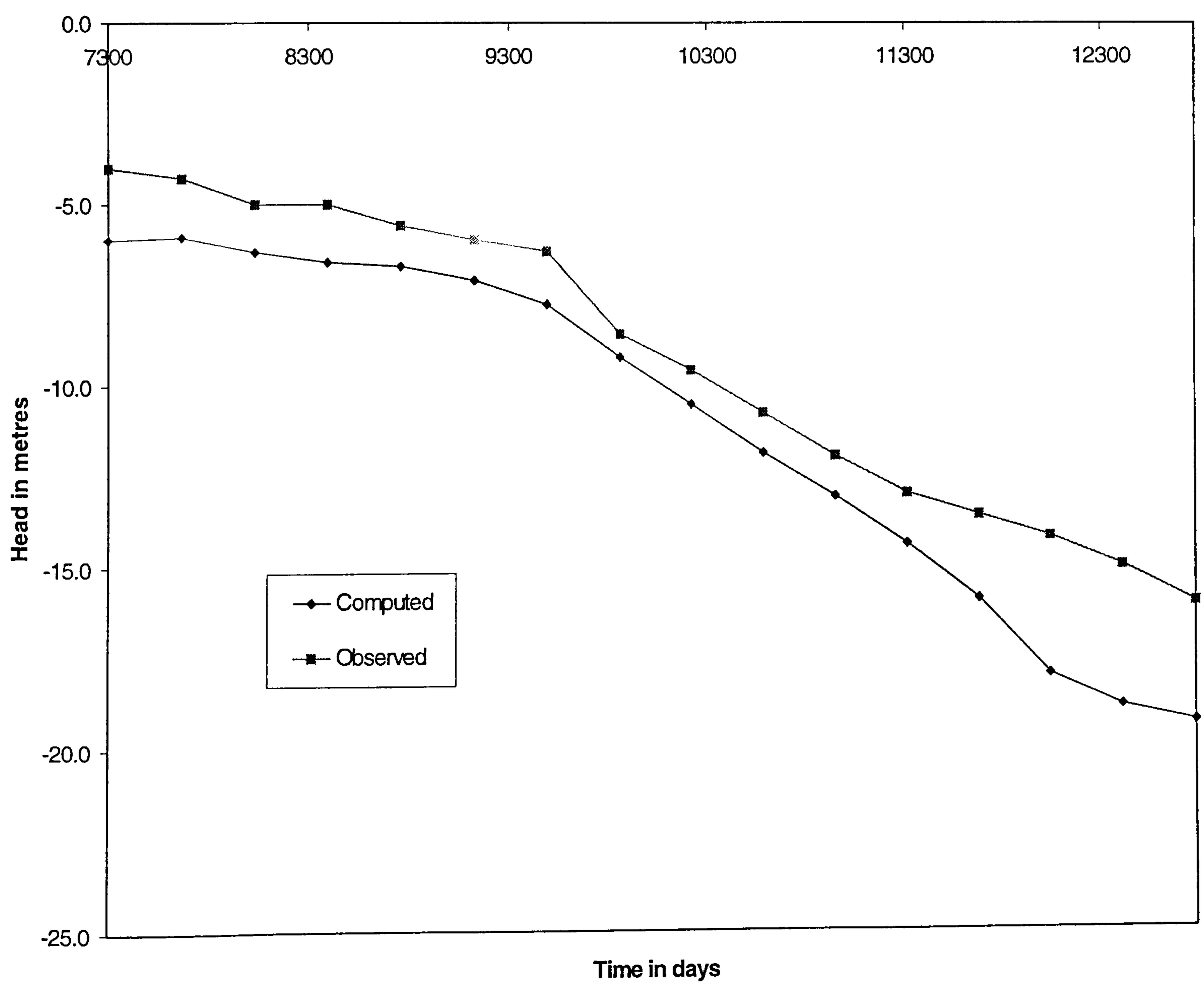


Figure 7.15 *Calibrated and observed hydrograph for the upper aquifer, DA-108/A (top) and DA-110 (bottom)*

Simulated water levels for the upper aquifer are compared with the observed pattern of piezometry throughout Dhaka, for the years for which the regional piezometry is available (Figure 7.9-7.12) and with hydrographs of individual observation boreholes (Figure 7.13-7.15).

There is a generally good agreement between observed and modelled piezometry and the hydrographs. The model successfully demonstrates the steady decline of the piezometric level during the past 20 years. The differences between modelled and measured values for most of the wells were within 3m. However, results at some places close to the river Buriganga such as for well DA-111/A (Figure 7.15) shows that differences exceeded 3m. The reason is believed to be the influence of the river Buriganga.

The good calibration suggests that the groundwater flow model is a good basis for modelling solute transport in the aquifers.

The model has been used to simulate the long-term response of groundwater abstraction from the Dhaka aquifer. Therefore, the short-term seasonal water level fluctuations have not been simulated.

The water balance components for the calibrated model for the year 1997 are compared with those of 1966 in Table 7.5.

Under 1997 conditions, the contribution from the polluted stretch of the river Buriganga is 142000 m^3/d (15%) whereas the combined contribution from the industrial areas Hazarbagh and Tejgaon and Jatrabari landfill area is 80000 m^3/d (8%).

After calibration and verification, the model was used to predict drawdown in the aquifer over the period from 1997 to 2020 assuming abstraction remains constant at its present day

Table 7.5 Comparisons of model flow balance for 1966 and 1997 for the Dhaka Dupi Tila aquifer.

Flow Components	**Volume (m^3/d)**		**(%) total inflow/outflow**	
	1966	**1997**	**1966**	**1997**
Inflows				
Recharge through Madhupur Clay	74 000	624 000	86	66
Induced recharge from rivers	10 000	284 000	13	30
(Polluted stretch of the river)	(5 000)	(142 000)	(6)	(15)
Storage changes	200	37 000	0.4	3
Outflows				
Municipal/industrial abstraction	75 500	920 000	89	97
Boundary outflow	5 000	26 000	6	2.5
Other abstractions	4 000	nil	4	0

value. The prediction run was made to assess whether the present rates of abstraction can be sustained over the next 20 years. The drawdown was calculated by running the model with the 1997 abstraction and recharge, and the year 1997 was used as the initial head for the prediction run. Other model parameters were kept at the values derived from the previous transient calibration. The result of the prediction run for the year 2020 is given in Figure 7.16. The result of the prediction shows that there will be only a minor lowering of water levels in the aquifers and that steady state conditions will be achieved by 2002.

7.4 Results and Discussion

The influence of the rivers in and around Dhaka city on groundwater levels is demonstrated to be an important factor controlling the overall water balance; in particular, the influence of the River Buriganga on water levels in the aquifer is significant. With comparable abstractions the decline in piezometric heads is less in old Dhaka than in areas further from

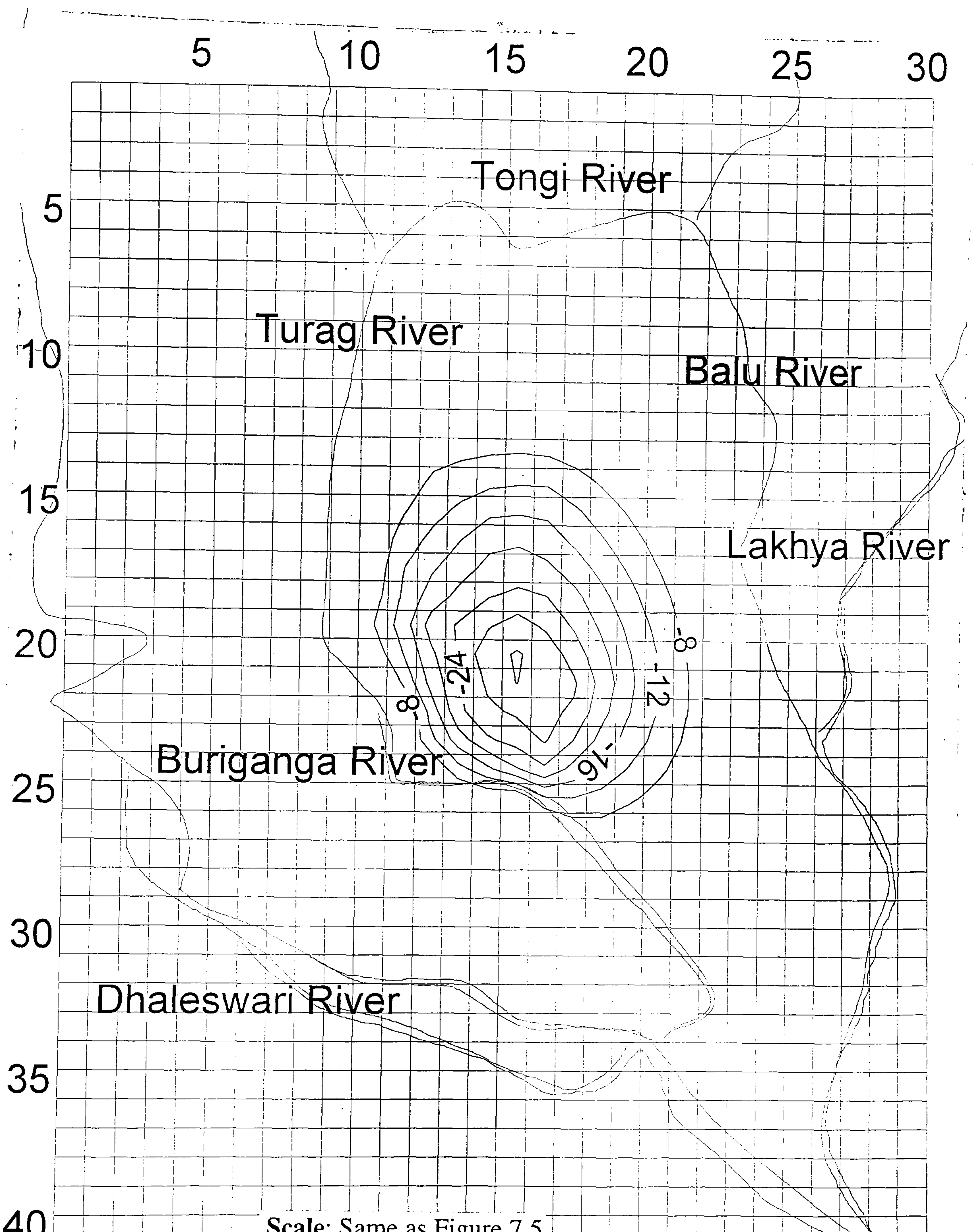


Figure 7.16 Results of the prediction run for the year 2020 (contour in metre)

the river, for example the Motijheel commercial area. The model shows the cone of depression expanding continuously with the increasing withdrawal of groundwater and predicts a large area across which the drawdown will be more than 20m by the year 2020. There will be a severe constraint on groundwater supply in some parts of Dhaka city where pumps will not be able to draw water from the aquifer under these future conditions.

The modelled water balance components (Table 7.5) show that the largest recharge contribution to the aquifers is from downward vertical leakage through the upper aquitard. This vertical leakage originates from natural as well as urban recharge. However, the volume of leakage inflow as a percentage of the total inflow has reduced from 84% to 66% during last 30 years, due to an increase in the contribution from the rivers. The proportional contribution of rivers to the aquifers recharge increases from 12% to 30% during the same period. The increase is directly attributable to the increased piezometric decline over the simulation period.

River-aquifer interaction has been determined as the dominant feature of many other aquifers during modelling studies e.g. the Chalk of Burkshire Downs in the UK (Rushton and Tomlinson, 1995). The interaction between rivers and aquifers can best be examined in detail using mathematical models (Kresic, 1997; Rushton, 1998). However there is still only limited experience in obtaining the field information required for a realistic modelling. In Dhaka a significant proportion of the induced recharge from the River Buriganga to the aquifer system is pumped out from boreholes, but the influence on river flows is likely to be unnoticed as it is less than 5% of total river flow.

Specifying the boundary condition along the rivers Buriganga, Turag, Balu and Lakhya rivers becomes the most significant limitation in the model. The hydraulic contact between river and aquifer is of great importance as it determines the exchange of water between the river and the aquifer and hence the extent of the cone of depression. However, the connection between the rivers and the aquifer is not well understood and only limited data are available to indicate the influence of river level fluctuations on groundwater levels. Available data beyond the river boundaries is insufficient to assess the influence of abstractions in the Dhaka in this region.

A limitation with respect to the MODFLOW code is the specification of specific yield. In Dhaka, specific yield values are often strongly depth-dependent, yet only a single value for each layer can be specified under MODFLOW. The drying-out and re-wetting of cells is not dealt with satisfactory by MODFLOW and causes instability during model operation.

Also, the MODFLOW code used for this study is limited in its capability to simulate some complex conditions such as surface flooding at various depths. Surface flooding, which may result in enhanced groundwater gradients during the monsoon season, can not be modelled with MODFLOW effectively.

Although the calibrated groundwater flow model should be viewed in the context of these limitations, it may be used as a basis for solute transport modelling using particle tracking techniques (MODPATH) and the three dimensional solute transport model MT3D. Specification for the particle tracking and solute transport models and results are described in the next Chapter.

CHAPTER 8 MODELLING SOLUTE TRANSPORT IN THE DHAKA AQUIFER SYSTEM

8.1 Introduction

Models of solute transport may consider a variety of processes, governing the advection, dispersion, and chemical fate of contaminants in groundwater. The term solute transport modelling refers to the use of computer-based numerical methods to obtain approximate solutions to the partial differential equations describing solute transport. (Zheng and Bennett, 1995).

Numerical modelling of contaminant transport, especially in three dimensions, is considerably more difficult than simulation of groundwater flow. If adequate data are not available, assumptions have to be made regarding processes and parameters which may invalidate the model results or make proper calibration impossible. A great deal of effort has gone into solute transport model development and documentation in recent years, and a number of practical solute transport models have become available. Among the most widely used of these are the USGS particle tracking code MODPATH (Pollock, 1989; 1994) and the three-dimensional solute transport model code MT3D (Zheng, 1990).

The main objectives of solute transport modelling in this thesis are: to investigate the ***relative*** significance of the different contaminant sources identified as a result of the field survey, to determine to what extent the heavy groundwater abstraction from the Dupi Tila aquifer during past two decades has contributed to the spread of contaminants in the aquifer, and to indicate possible future development in the extent of the contaminated groundwater plume.

8.2 Modelling Software

8.2.1 MODPATH

The USGS particle tracking code MODPATH (Pollock, 1989; 1994) was used to calculate particle movement and travel times within the steady-state three-dimensional flow field generated by MODFLOW. The cell-by-cell flow terms from the calibrated steady-state MODFLOW simulation were used as an input to MODPATH. MODPATH takes the calculated head distribution from MODFLOW and uses it to compute a velocity distribution, which is then used in turn to trace out path lines for the particles. The programme MODPATH tracks the movement of infinitely small imaginary particles placed in the flow field. To predict flow paths and travel times with MODPATH, hypothetical groundwater particles are placed in the flow system. Particle movement can be tracked forward to simulate the movement of contaminants from source areas, and backward to describe borehole catchment areas.

Although the MODPATH simulations provide an assessment of solute movement by advection, incorporation of other important transport processes (dispersion, sorption, and degradation) into a contaminant transport model allows a more thorough and detailed examination of contaminant fate in the aquifer. Therefore the code MT3D was selected for a fuller treatment of contaminant transport in the Dhaka aquifer.

8.2.2 MT3D

MT3D software was selected to model solute transport in the Dhaka aquifer system since it provides an easy link with MODFLOW. MT3D is widely accepted as a suitable tool to assess transport of solutes in groundwater. It is a modular, three-dimensional, solute transport model incorporating advection, dispersion and chemical reactions of dissolved constituents in groundwater system (Zheng, 1990). The model solves the three-dimensional advective-dispersive-reactive equation with a choice of three methods: the method of characteristics (MOC), the modified method of characteristics (MMOC) and a hybrid of these two methods. This third option is referred to as the hybrid method of characteristics (HMOC) by Zheng (1990). The hybrid method was used for this study because this method attempts to combine the strengths of the MOC and the MMOC techniques, by using an automatic adaptive scheme conceptually similar to that proposed by Neuman (1984). By selecting appropriate criteria for controlling the switch between the MOC and MMOC schemes, the adaptive procedure can provide accurate solutions to transport problems under a variety of flow conditions. This study used MT3D_DOD, a recent version of the program developed at the University of Alabama for the US Army Corps of Engineers.

A three-dimensional transport model using MT3D was applied to simulate point and non point-source contamination, and to explore the range of expected concentrations at various depths, locations and times for a variety of possible contaminant sources.

8.3 Model Parameters

The value of the model parameters used in the MODFLOW simulations remained the same for the contaminant transport modelling. In addition to all flow parameters, effective porosity (n_e), the porosity through which flow can occur, is required by MODPATH and MT3D to calculate the average linear velocity of groundwater flow. This velocity is needed to track water particles as they move through the porous media. For the top Madhupur Clay layer, 10% effective porosity is estimated for the model. The effective porosity for all other layers was based on published values for similar (sand) lithologies and is estimated at 15%.

Dispersion is an important process incorporated in MT3D though not in MODPATH, which refers to the spreading of contaminants due to aquifer heterogeneities and mixing. Because the invading solute-containing water is not all travelling at the same velocity, mixing also occurs along the flow path. This mixing, in combination, is called mechanical dispersion, and it results in a dilution of the solute at the advancing edge of flow (Fetter, 1993). Dispersion may occur in longitudinal and transverse directions. Transverse dispersion reduces concentration at all points behind the advective front, while longitudinal dispersion will do so only at the front of the plume. Dispersion is characterised by the parameter dispersivity, α, with dimensions of length (Domenico and Schwartz, 1998) and is the mathematical product of dispersivity and advective velocity. The magnitude of the dispersivity varies widely for different lithological types (Gelhar *et al.* 1992) and is also dependent on the scale of the problem being considered (Anderson, 1979; Pickens and Grisak, 1981). A value of 20m was assumed for the longitudinal dispersivity of all layers in the solute transport model of the Dhaka groundwater system, consistent with published values for alluvial sediments and the scale of contaminant movement (Spitz and Morneo, 1996).

In addition, a solute in water will move from an area of greater concentration toward an area where it is less concentrated under the chemical potential gradient. This process is known as molecular diffusion, or diffusion. The effect of molecular diffusion can not be separated from the effect of mechanical dispersion in flowing groundwater. The two are therefore combined to define a parameter called the (longitudinal) hydrodynamic dispersion coefficient (D_L).

Sorption is a process which refers to the mass transfer between contaminants dissolved in the groundwater and sorbed on the porous medium. Adsorption describes the adhesion of molecules or ions to the grain surface in the aquifer. The release from the solid phase is called desorption. In MT3D, only equilibrium-controlled linear and non-linear sorption is included (Zheng, 1990), which implies that the sorption and desorption of contaminants is always at equilibrium. The impact of sorption on the movement of contaminants can be incorporated in the model through the use of a retardation factor, R, which is determined by the sorption isotherm. For the case of the conservative solute, chloride, sorption has not been simulated in the model and therefore the retardation factor is set to the default value of 1 (Zheng, 1990).

Other chemical reactions, decay and degradation processes have not been included in the model simulation.

8.4 Boundary and Initial Conditions

As in the case of the flow equations solution, initial and boundary conditions are required for the solution of the transport equations (Anderson and Woessner, 1992; Spitz and Moreno, 1996; Zheng and Bennett, 1995). Generally, there are three types of boundary condition used in transport models: (1) Concentrations are specified along a boundary, (the Dirichlet condition or concentration type boundary); (2) concentration gradients are specified across a boundary, (the Neumann condition); and (3) both concentrations along a boundary and concentration gradients across the boundary are specified yielding a combination of (1) and (2), called the Cauchy condition.

In flow modelling, a Dirichlet boundary is a specified-head boundary; a boundary condition of this kind acts as source providing water to the domain, or a sink removing water from the domain. Similarly, a specified-concentration boundary in a transport model acts as a source from which solute mass enters the domain, or as a sink at which solute mass leaves the domain. Leaky structures, such as landfills, polluted ponds and infiltration beds can be represented by this specified concentration boundary and therefore this boundary type was used in the model.

The initial conditions are the concentration conditions at the starting time of the simulation. This requires detailed information on the location and history of the contaminant sources, which is rarely available and is not so in the case of Dhaka. The simplest way to do this would be to use the existing field data directly as the model input; however, the concentration distribution of an existing plume is rarely known in sufficient detail to allow this approach. Due to a lack of data in the Dhaka aquifer, transient simulations under MT3D started with zero initial concentrations.

8.5 Contaminant Source Description

MODPATH

Using the MODPATH programme, hypothetical particles were placed in (a) the upper levels of the groundwater flow system close to the influent river boundary of the River Buriganga and (b) elsewhere within the urban area (Table 8.1). The head distribution following the stress period 33 of the MODFLOW output, simulating groundwater flow conditions in 1997, were used for the MODPATH runs. As the top layer (the Madhupur Clay) was dry under these flow conditions, the particles were placed at the bottom of that layer. Then the particles were tracked forward to the discharge points. The MODPATH simulations were run for 50 years from 1997 under this steady state flow system. The results are shown in Table 8.3 and Figures 8.1-8.4.

MT3D

Contaminant transport was modelled using MT3D under three different scenarios (Table 8.2). The first scenario represents the River Buriganga as a source of contamination and assumed a concentration of 1000mg/l of a conservative contaminant in the water, over the polluted stretch of the river which supplies water to the aquifer as induced recharge.

The second MT3D scenario represents localized point-source contamination with concentration equal to 1000mg/l of contaminant concentration in the shallow groundwater. Two industrial areas, Hazaribagh and Tejgaon, and one landfill site,

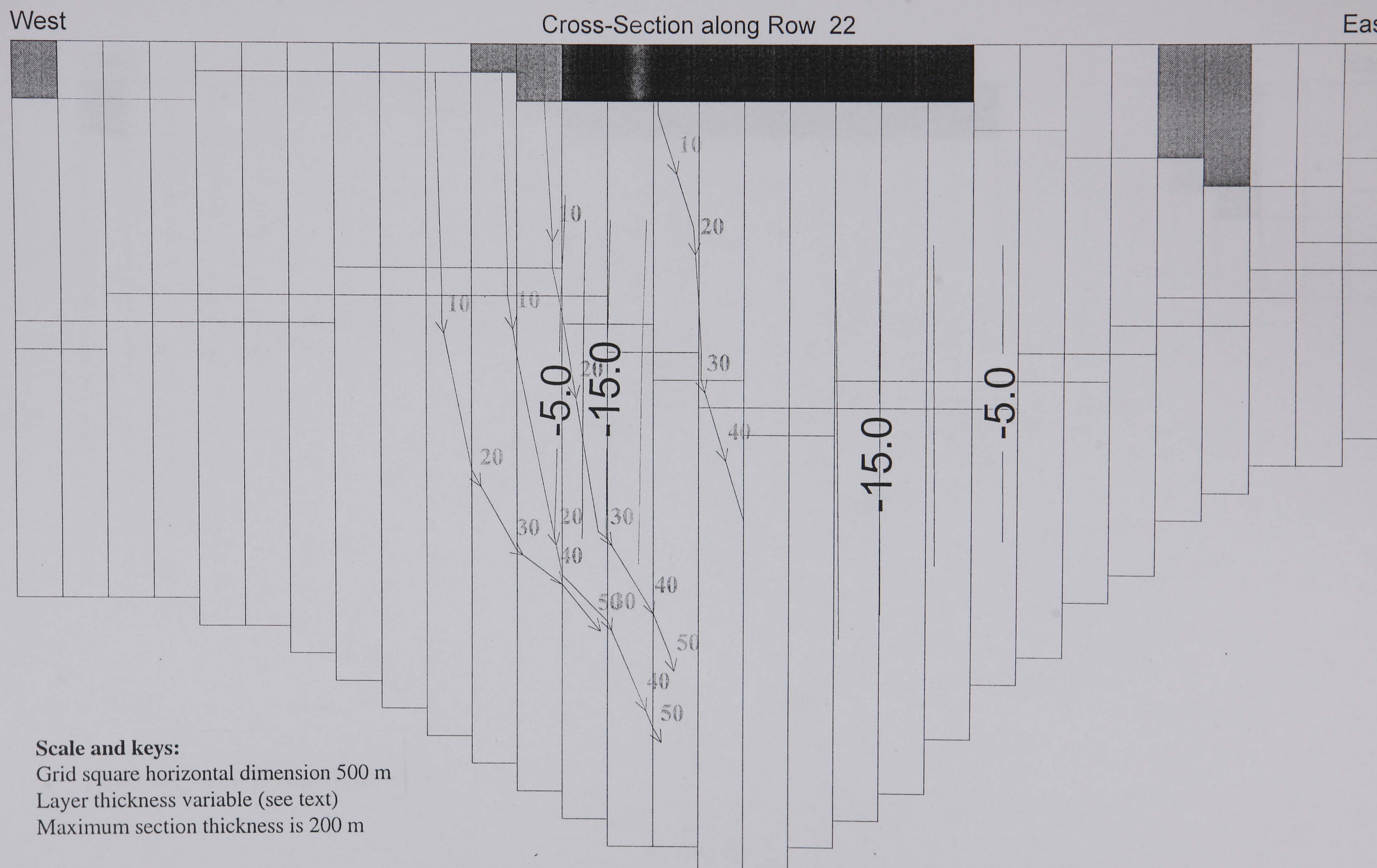


Figure 8.1 Profile view of simulated particle path, river Buriganga (arrow indicates time in years)

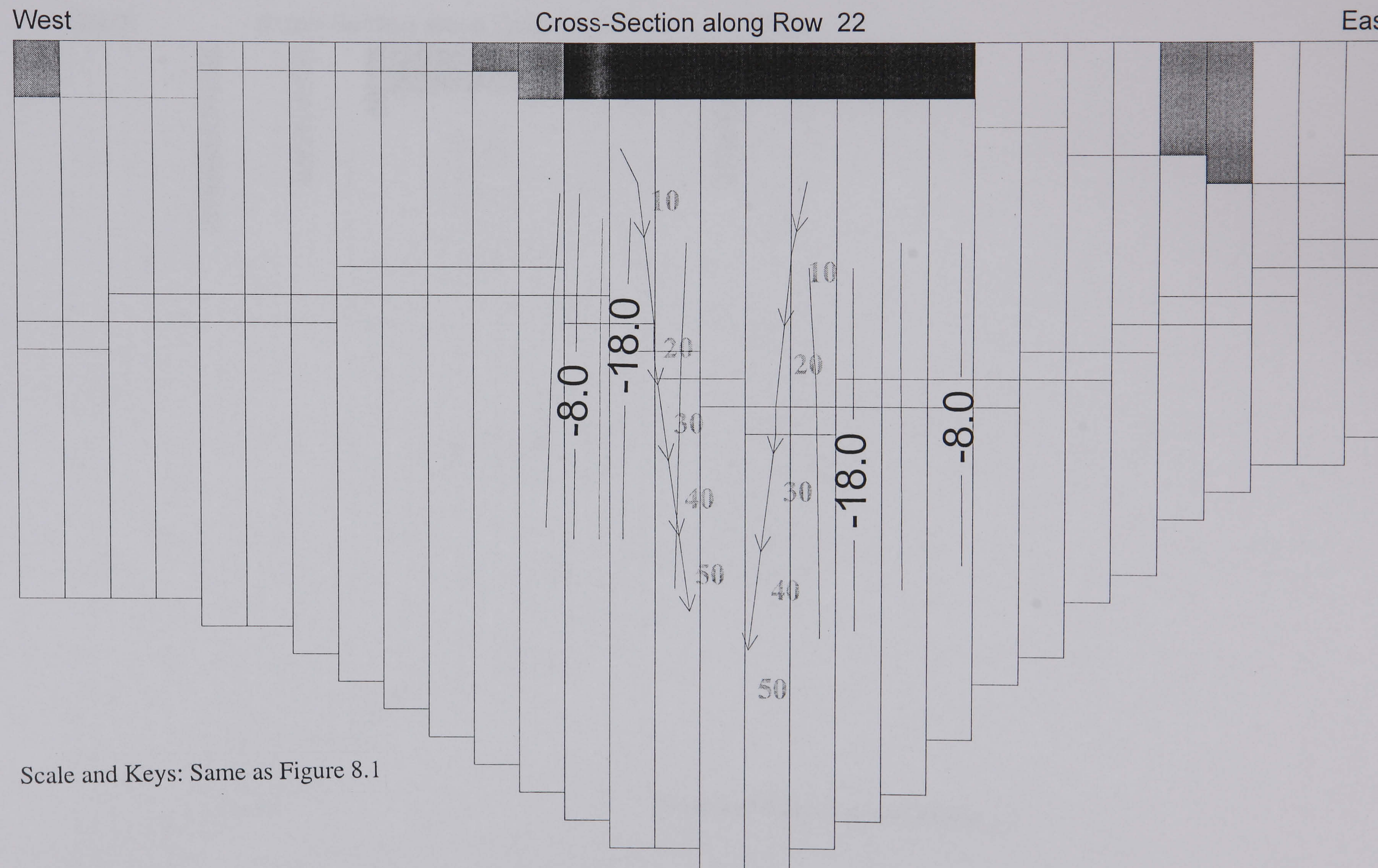


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***Figure 8.2** Profile view of simulated particle path, Industrial area (arrow indicates time in years)*

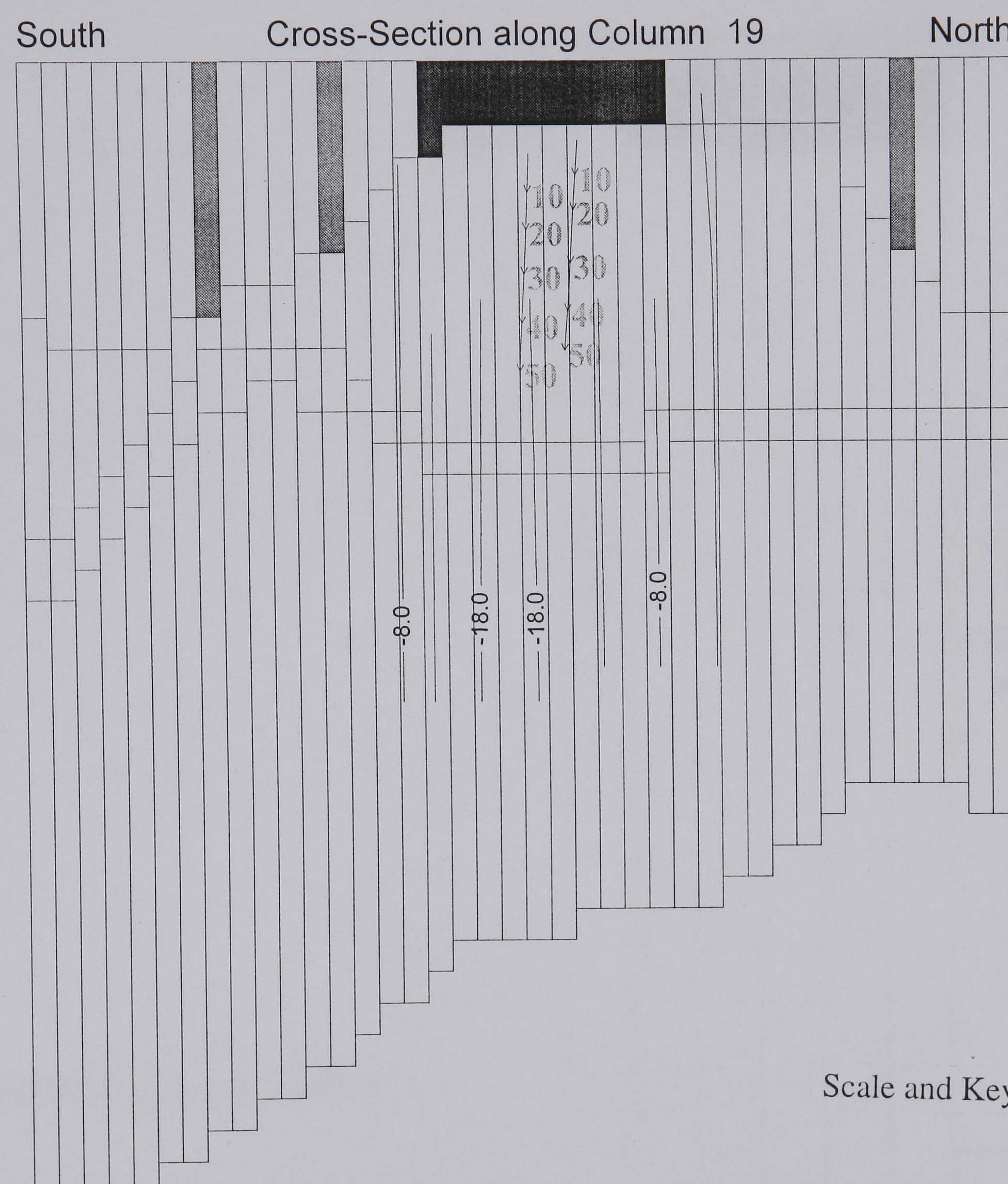

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Figure 8.3 Profile view of simulated particle path, landfill area (arrow indicates time in years)

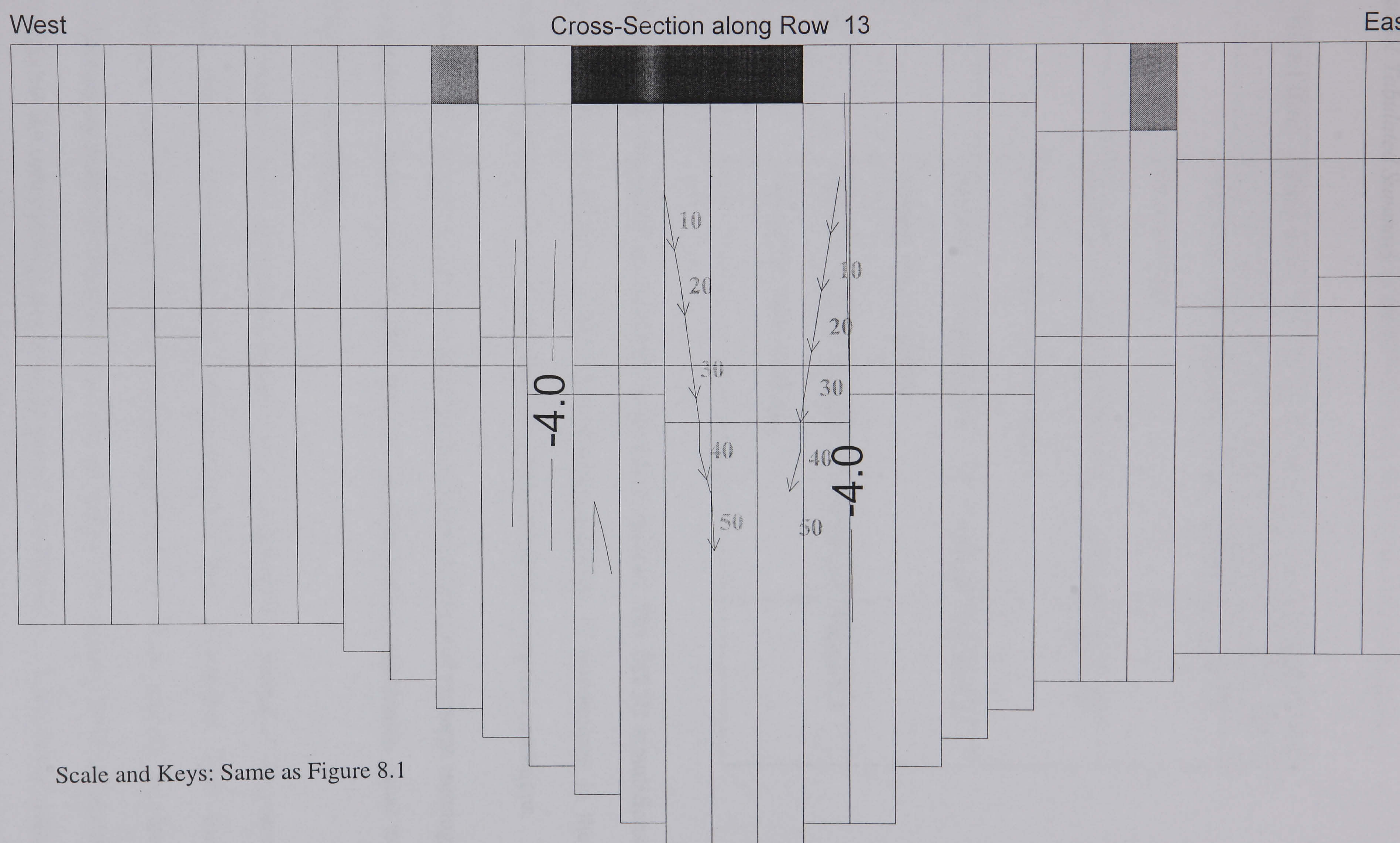

Figure 8.4 *Profile view of simulated particle path, central Dhaka (arrow indicates time in years)*

Table 8.1 Tabulated Summary of MODPATH run in the Dhaka aquifer system

Model Run	Purpose	Result
1	Simulate contamination from induced river recharge	Figure 8.1
2	Simulate contamination in vertical leakage from an industrial area	Figure 8.2
3	Simulate contamination in vertical leakage from a landfill	Figure 8.3
4	Simulate vertical leakage of widespread low quality urban recharge	Figure 8.4

Jatrabari, were considered as localized contaminant sources. The MT3D simulations were again run for 34 years to show how the concentration of contaminant in the groundwater develops with time under these different contamination source conditions.

The third scenario represents city-wide, urban contamination, in which all recharge entering the groundwater system over the urban area for 34 years has a concentration equal to 1000mg/l of contaminant.

For each scenario, the contaminant transport was simulated for a period of 34 years between 1964 to 1998, using transient groundwater flow simulations from the MODFLOW runs. The concentration of contaminated surface water sources e.g. the canal discharging industrial effluents to the river Buriganga is more than 1000mg/l (up to 7000mg/l) but the concentration in river water is less than 1000mg/l. Therefore the value of 1000mg/l was selected as a justifiable indicative source concentration.

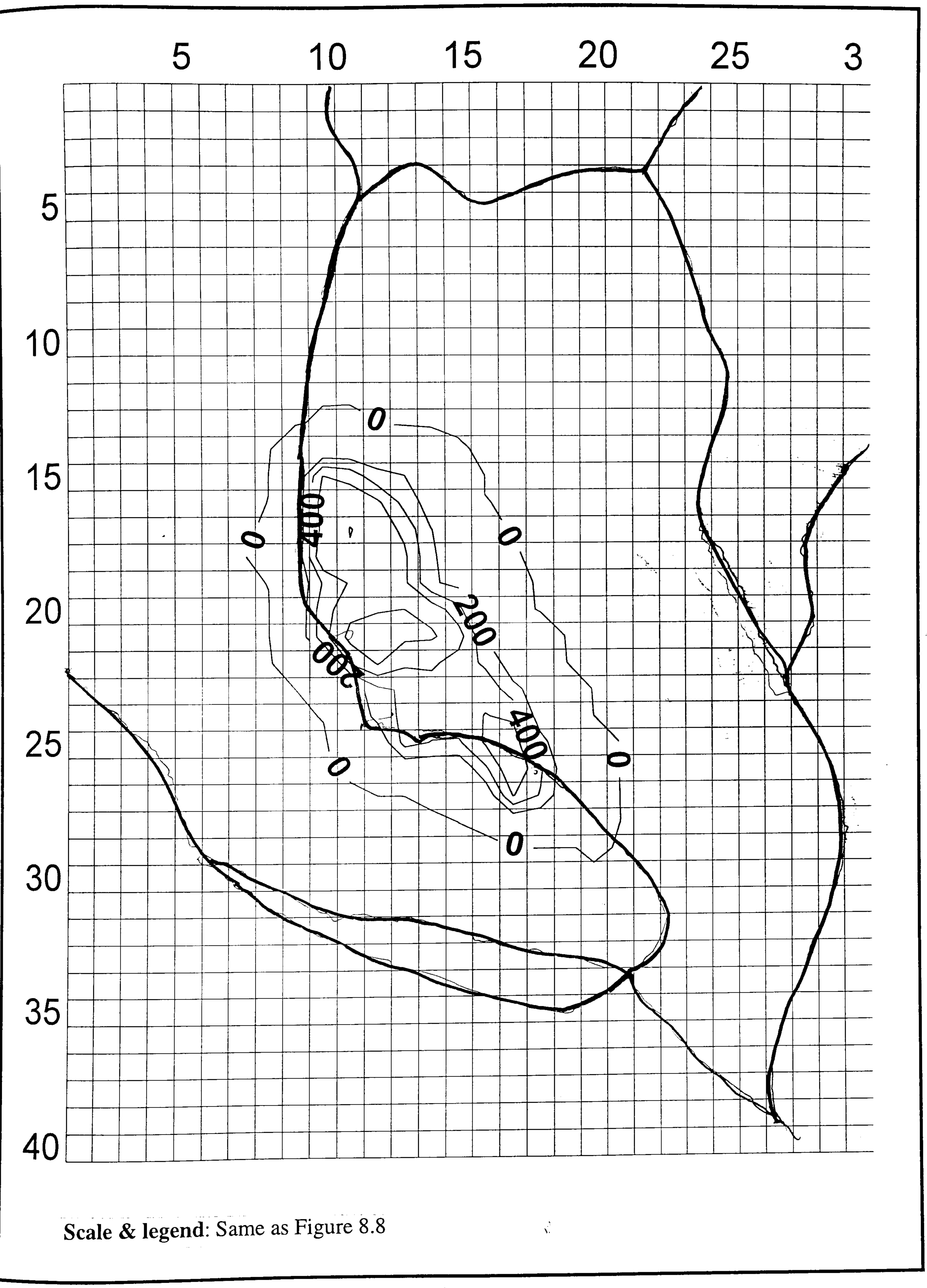

Figure 8.5 Simulation of the river source contamination(mg/l) under MT3D for the year 1997

Scale & legend: Same as Figure 8.8

Figure 8.6 Simulation of industrial area contamination(mg/l) in the aquifer under MT3D for the year 1997

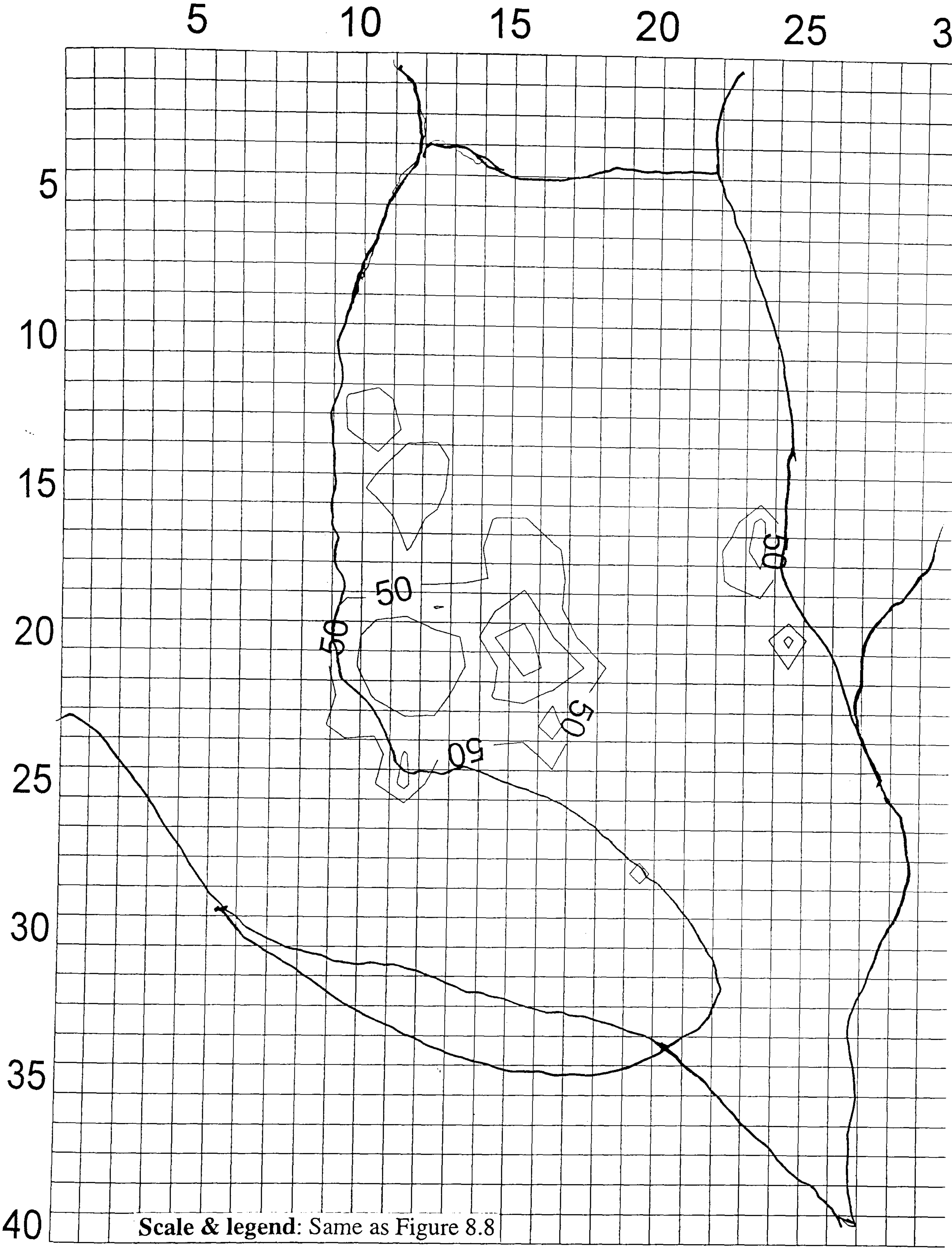

Figure 8.7 *Simulation of general urban recharge contamination (mg/l) in the aquifer under MT3D for the year 1997*

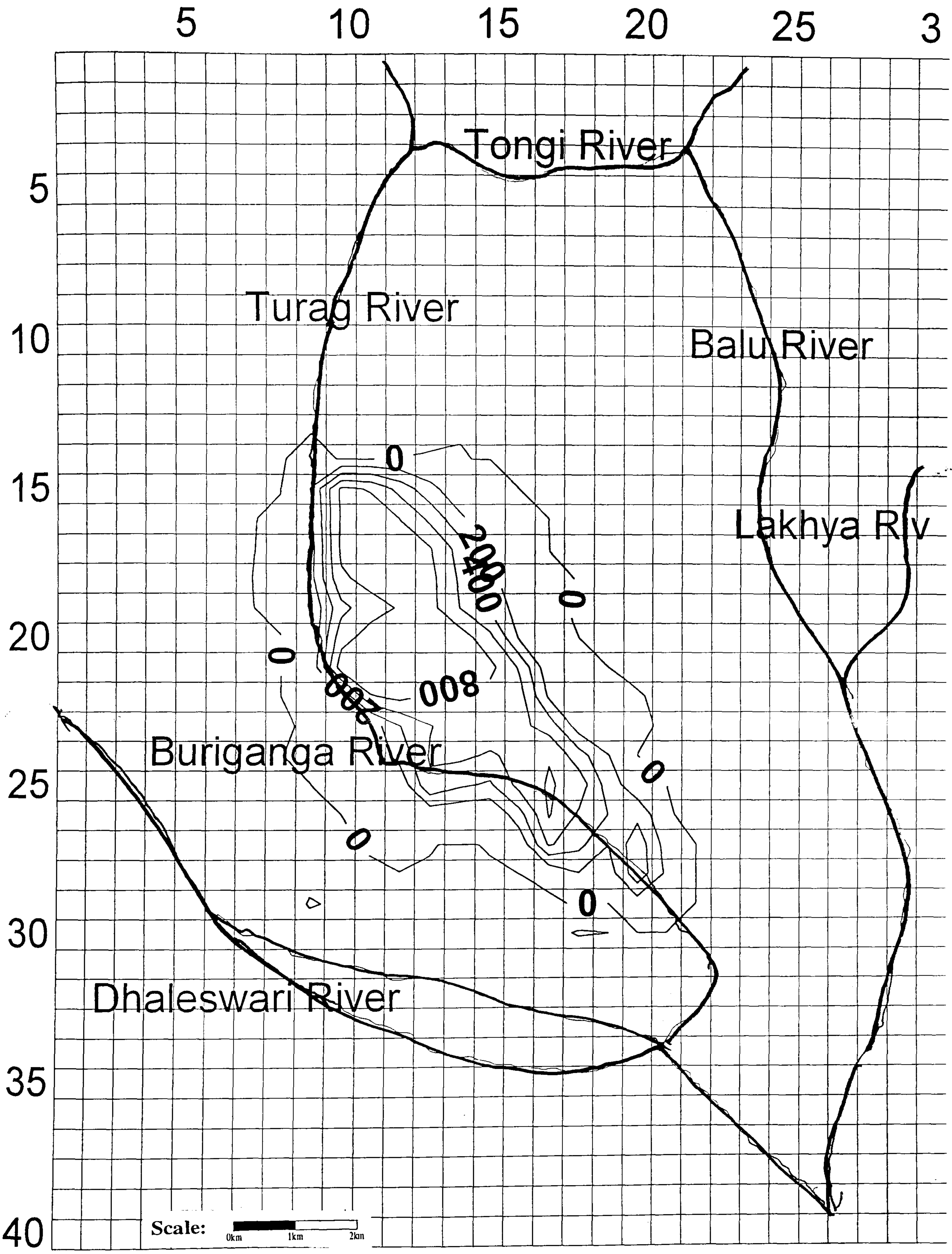

Figure 8.8 Prediction of river source contamination(mg/l) in the aquifer under MT3D for the year 2020

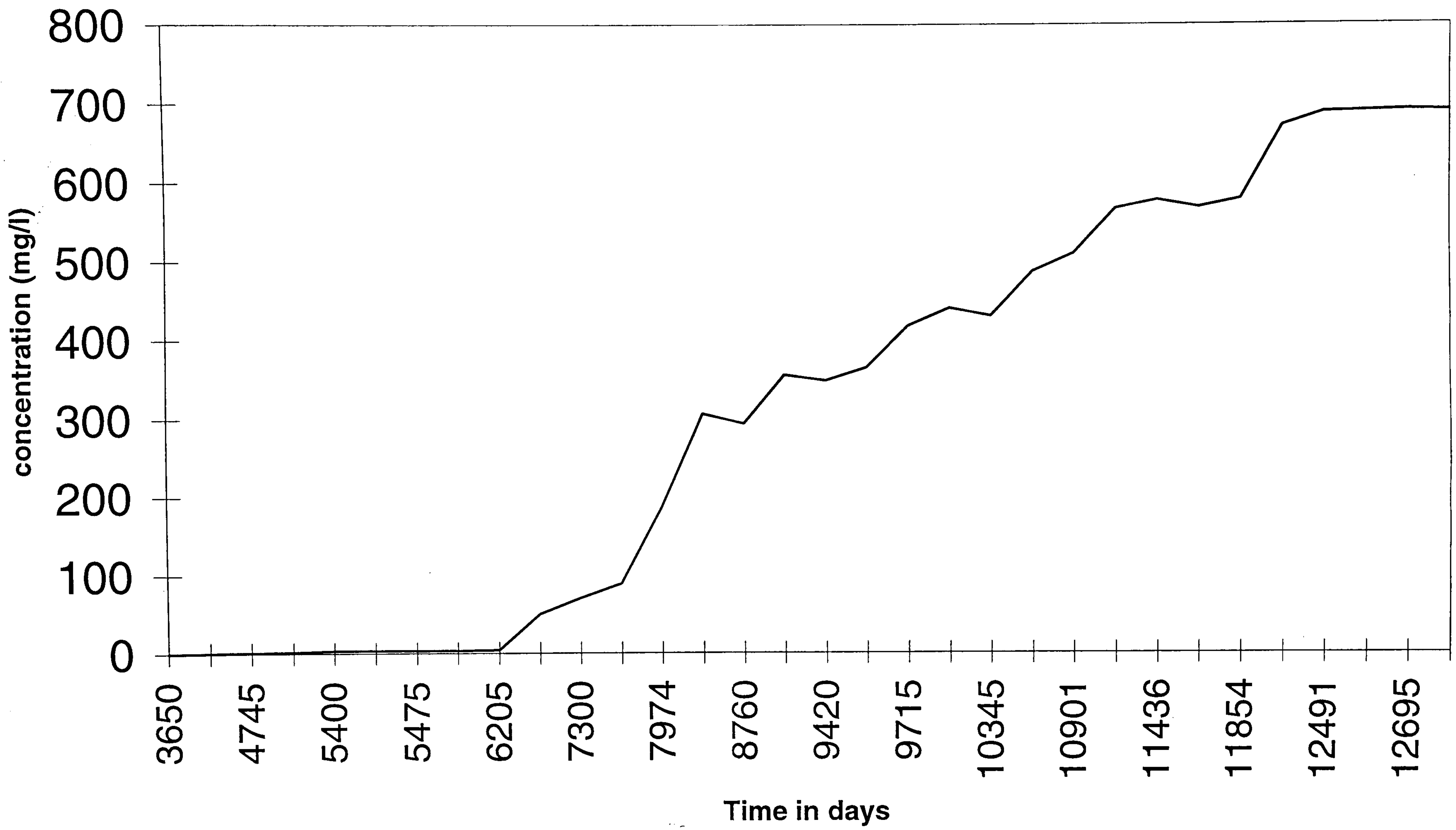

Figure 8.9 *Simulation of contaminant concentration (mg/l) at a monitoring point*

The scale of the flow models, which use a grid spacing of 500 m *500 m, is too coarse for accurate contaminant transport modelling. Numerical dispersion is the major obstacle encountered in the finite difference method where the discretization grid is too coarse. Numerical dispersion refers to artificial dispersion caused by errors associated with the discretization of the problem domain. Zheng (1990) explains the mathematical origin of numerical difficulties in detail. To reduce numerical dispersion and to illustrate the scale of its effects, a finer grid called the telescopic mesh refinement (TMR) or grid zooming procedure can be used under GV. TMR is the process of creating a more refined model within a subregion of a lager-scale model. This is done to obtain greater resolution of the contaminant plume and to use smaller values of dispersivity. However, the version of GV used for this model was limited to its capability for creating and running transient TMR, and a limitation of the solute transport model is that it includes a component numerical dispersion that has not been quantified.

Table 8.2 Summary of the MT3D run in the Dhaka aquifer system

Model Run	**Purpose**	**Result**
1	Simulate river source	Figure 8.5
2	Simulate individual Industrial and landfill sources	Figure 8.6
3	Simulate general urban recharge source	Figure 8.7
4	Prediction of future contamination from contaminated river recharge, to 2020	Figure 8.8

8.6 Predictive Use of the Model

Particle tracking can be applied to evaluate travel times of contaminated groundwater from sources to areas of interest. Although this type of analysis is only approximate, when based on advection only, it is nevertheless extremely useful as an alternative to full-scale solute transport modeling for many problems. The MODPATH model under this study estimates the predicted time required for the particles to travel from the industrial areas or landfills to the main aquifer. The MODPATH model was run as steady state, so under the present flow condition, the time required for particles to reach the main aquifer is within 30-40 years. However, this is an underestimate of the actual situation.

Under MT3D, the model was run for predictive purposes over the period from 1997 to 2020 for the first scenario, assuming that the input concentrations remain constant, and using the modelled concentration for the year 1997 as the initial concentration for the prediction run. The result of the prediction run is shown in Figure 8.8.

8.7 Results and Discussion

MODPATH Results

Several runs using MODPATH under steady state conditions were used to simulate particle movement from particle sources (Table 8.1). A summary of the MODPATH results is shown in Table 8.3. Analysis of the particle tracking indicates that the particles moving from the industrial areas under vertical leakage take considerably more time to reach the lower aquifer than the particle from close to the river source (Hasan *et al.*, 1999). Particles released at the bottom of the Madhupur Clay move almost vertically downward to reach the lower aquifer. Profile views of particle paths representing travel times in years are displayed in Figure 8.1-8.4. Some particles do not leave the upper part of the aquifer within 50 years. The MODPATH simulations successfully demonstrate the relative vulnerability of the Dhaka aquifer to each of the two types of induced recharge.

Table 8.3 Transport times for contaminants entering the aquifer by using MODPATH

Source	**Particle transport times in years**	
	To base of Upper Aquifer	To PWS borehoels
Close to river Buriganga	10 years	15-20 years
Hazaribagh Industrial Area	25 years	30-40 years
Landfill Area	>50 years	> 50 years
Central Area	35 years	45-50 years

MT3D Results

The MT3D modelling demonstrates the impact of the river Buriganga as a source of contamination reproducing the pattern of groundwater quality variation observed in the aquifer in 1996 (Figure 8.5). As of 1997 the contamination has spread over approximately 20 km^2. Travel time for the contaminant to reach the aquifer from the River Buriganga is around 15-20 years, much less than the travel time for vertical leakage through the Madhupur Clay. There are insufficient data to calibrate the solute transport model properly in transient mode and therefore no attempt was made to calibrate the model. However, the results of the solute transport model compare well with the pattern of EC distribution in 1996 in the main aquifer (Chapter 5). The result of simulated transient contaminant concentrations at a monitoring point in South West Dhaka is given in Figure 8.9, and this is of a similar form to the small amount of available historical data (e.g. Figure 5.2 of Chapter 5). The solute transport modelling work has therefore identified induced river recharge as the primary potential source of pollution for the southern side of the Dhaka aquifer.

The prediction run using the MT3D from 1997 to 2020, assuming the constant concentration of the first scenario, indicates that the contaminants will spread further with time.

The impact of vertical leakage and point sources of contamination within the city area are shown in Figure 8.6. The modelling indicates that significant additional threats to groundwater integrity could also come from land-based pollution sources such as the Hazaribagh and Jatrabari areas, but not for a considerable time, i.e. not before 2030. These results are consistent with the depth profile of groundwater quality observed in the aquifer.

The modelling results confirm that the field observations of groundwater quality variations in the Dhaka aquifer could be the result of the combined effect of recharge by polluted river water and enhanced vertical leakage from polluted industrial sources. However, the influence of the River Buriganga as a source of pollution for public supply wells in the deep aquifer close to the river is stronger than the city-wide pollution sources. The effect of the city-wide sources will not become generally apparent for approximately another 30 years.

The source of specific organic contaminants may be an exception to this generalization. Dense non-aqueous phase liquid may penetrate an aquifer more quickly and deeper than inorganic solutes. Observation of the presence of organic contaminants in the deep aquifer are not inconsistent with the modelling results, but act as a warning that the threat of these organic contaminants should be taken more seriously (see Chapter 6).

One of the most important hydraulic parameters for modelling contaminant movement is effective porosity. It is extremely difficult to measure values of effective porosity, which are usually based on specific yield or are assumed for a particular lithology, or on calibration of a solute transport model. A value of 20m was assumed for longitudinal dispersivity, which was not based on any measurements, but is consistent with published values for this type of lithology and scale of contaminant movement. The reliability of the results and confidence in the predicted contaminant movement would be improved if the level of uncertainty of these features were reduced.

This is the first numerical model for Dhaka aquifer which incorporates both flow and solute transport. The modelling results provide the opportunity for assessing the vulnerability of the Dupi Tila aquifer and the impacts of different aquifer management strategies for the Dhaka aquifer.

Chapter 9 Summary discussion, Conclusions and Recommendations

Summary and Conclusions

The reader is referred to the research objectives listed in Section 1.5.

The Dupi Tila aquifer beneath Dhaka city is vulnerable to contamination from a variety of point and nonpoint sources of pollution. Heavy exploitation of the aquifer in the City has led to continuing water level decline and modification of the recharge regime, which is in turn having a detrimental effect on the groundwater quality. The intensive groundwater abstraction has led to induced recharge from rivers and enhanced vertical leakage from regions containing contaminated land.

Groundwater quality variations throughout the Dhaka region, with depth in the aquifer and with time have been defined. The detailed groundwater quality distribution in the aquifer indicates that the aquifer in the South West of the city is particularly vulnerable to pollution. Modelling results show that this is due to induced river recharge. Vertical leakage is a threat to the aquifer more generally, risks being greater where particular sources of contaminants are concentrated e.g. beneath industrial areas and landfills. Beneath two industrial areas, Hazaribagh and Tejgaon, the aquifer is contaminated by industrial chemicals including TCE, PCE, chloroform and benzene. Vertical hydrochemical profiles show that urban pollution has reached the upper levels of the aquifer within the city in places, but not the level of groundwater abstraction except in isolated cases. Further deterioration of the groundwater quality is inevitable as contaminated water in the confining layers and upper part of the aquifer system moves down to the main aquifer more widely.

The sustainability of the groundwater abstraction in Dhaka in the long term is in question. As the city continues to expand, the Dupi Tila aquifer beneath the city may be unable to meet the rising demand for water. Yet the aquifer has the capacity to supply groundwater at sustainable rates and of reliably good quality if protected properly. Protection for use as a strategic supply of high quality water is a preferable option for the aquifer than its continued deterioration city-wide.

In Dhaka, despite the hydraulic benefits of induced river recharge, aquifer storage is being depleted and water levels in the aquifer continue to decline. While the aquifer characteristics are favourable and the borehole designs remain appropriate, how long this situation is acceptable is an economic question. Careful monitoring of both the piezometry and the groundwater quality is an essential adjunct of continued development.

Groundwater flow modelling suggests that a new hydraulic equilibrium will be established in the aquifer within five years, with abstraction balanced by induced recharge and a reduced proportion of vertical leakage, if further development of the aquifer is restricted. Controls on abstraction would be required to enforce this. Careful monitoring is also necessary to validate the model predictions, and as a tool and test of management decisions.

Preliminary indications are that the deterioration in groundwater quality is minimised by attenuation within the aquifer. Yet contrary to initial assessment of the aquifer vulnerability, this study demonstrates that the Madhupur Clay Formation does not provide unlimited natural protection from urban and industrial contaminants. This has important implications for the management and protection of the Dhaka aquifer. More regular and more detailed monitoring of groundwater quality is required to confirm this.

A solute transport model, linked to the model of groundwater flow, has been developed to enable predictions to be made, to give confidence in the extrapolation of groundwater quality trends and to direct the monitoring programme. Contaminant transport modelling demonstrates that a general deterioration of groundwater quality is inevitable even if all the sources of contamination are removed immediately. Contaminants originating as widespread vertical leakage of low quality urban recharge will take approximately 35-40 years to reach the level of abstraction of the water supply boreholes. The groundwater flow and solute transport model could be used as a planning tool in water resources management and to guide groundwater quality monitoring as part of a protection policy for this strategically important aquifer.

Recommendations

The traditional reliance on groundwater for water supply in Dhaka is not sustainable in the long term. To safeguard the aquifer as a source of high quality water of strategic importance, a conjunctive surface and groundwater management plan should be developed. Additional development of groundwater from the Dhaka aquifer should be sanctioned with caution. As discussed earlier, the following specific recommendations are proposed regarding the vulnerability of the Dhaka aquifer, in order to protect its groundwater resources.

1) The existing water level monitoring programme of the BWDB in the Dupi Tila aquifer in Dhaka is not adequate. The borehole monitoring network should be expanded to cover the entire area between the rivers Buriganga, Balu, Turag and Tongi. Shallow water level decline in multiple aquifer systems can be used to indicate overabstraction at an early stage (Rushton, 1986; Hasan *et al.*, 1998). Therefore, the water level monitoring boreholes should be completed to monitor water levels at different depths, including in the Madhupur Clay as well as in the upper and lower levels of the aquifer. In addition to manual recording, it is strongly recommended that some autographic recorders should be used for water level monitoring.

2) The present groundwater quality monitoring in the Dupi Tila aquifer in Dhaka is also inadequate. The number of BWDB water quality monitoring boreholes should be increased from two to at least twenty-five to cover the entire city, area with concentration at the vulnerable areas adjacent to river Buriganga and the major industrial areas and landfill sites. To identify the vertical distribution of both organic and inorganic pollutants, depth-specific monitoring boreholes should be installed within the Madhupur Clay and the upper and lower levels of the aquifer, particularly in the more vulnerable industrial and landfill areas in the city.

In addition, DWASA itself should monitor at least 25% of their public supply wells on a regular basis. Samples from these wells, which are continuously pumped at a high rate, indicate the general water quality in the aquifer averaged over larger volumes of aquifer than the samples from targetted monitoring boreholes.

Monitoring of groundwater quality samples from both type of borehole should include major, minor and trace components and representative organic contaminants. Certain indicators and general parameters such as EC, pH, DO and TDS should be monitored at least once a month in the vulnerable areas such as Hazaribagh, Tejgaon, Jatrabari and Mugdapara. Samples from public supply wells should be analysed for all major, minor and trace components at least twice a year. In addition to the inorganic analyses, samples from the industrial and landfill areas should be analysed for volatile organic compounds and heavy metals.

At the start of the monitoring borehole installations, a survey should be undertaken on all DWASA public supply wells, private wells and BWDB water level and quality monitoring wells to give accurate geo-referenced locations.

3) In response to expansion of urban and industrial development around Dhaka city, surface water quality monitoring by DoE should also be expanded.

4) A special study should be undertaken jointly by DWASA and BWDB to confirm the occurrence and pattern of organic pollution in the public supply wells, and to identify the detailed nature and extent of this problem. The study should include special sampling from a range of depths to identify the vertical distribution of organic pollutants. The study should include an audit of the number, location and nature of potential polluting industries and other potential pollution sources.

5) Although the influence of River Buriganga on the aquifer in Dhaka city has been demonstrated by groundwater flow and solute transport modelling, there are very limited data to describe the hydraulic contact between the rivers and the aquifer. Therefore, it is proposed that observation wells should be installed in the aquifer on the southern bank of the River Buriganga, south of Dhaka, and pumping tests and sediment analyses carried out in order to understand the role of rivers to a greater extent.

6) To protect the Dhaka aquifer, there is a need to manage land use and other development activities carefully in the vulnerable areas mentioned above, in accordance with standards that are becoming widely accepted as components of groundwater protection strategies. Borehole catchment modelling is not required as the whole of Dhaka is effectively within the combined catchments of the public water supply wells. To stop the practice of disposing industrial and municipal wastes in low-lying areas, it is strongly recommended that an initiative should be taken to draft environmental legislation to control the handling, deposition and monitoring of solid and liquid wastes, both from domestic and industrial sources. Industries should be responsible for treating their own wastes to an acceptable standard before disposal. Appropriate water law should be created to protect water resources from contamination.

7) Finally, the DWASA, the sole agency responsible for water supply in Dhaka city, operates without a single formally trained – hydrogeologist. It is proposed that the DWASA should set up a water resources research, development and management unit under a trained hydrogeologist, to take care of all hydrogeological aspects of management of water resources in Dhaka, including responsibility for both groundwater quantity and groundwater quality.

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Appendix 3.1 "Whole rock" chemical composition of the Dupi Tila sediments from various places (After Islam, 1996)

Wt%	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
SiO2	87.52	80.98	81.78	83.88	83.98	82.35	72.16	81.17	74.44	75.97	74.33	76.54
Al2O3	5.66	9.06	8.75	7.64	7.53	7.89	12.87	7.43	10.63	9.71	11.16	10.70
MgO	0.11	0.28	0.25	0.18	0.18	0.21	0.78	0.45	0.71	1.17	0.55	0.56
CaO	0.01	014	0.14	0.15	0.17	0.15	0.11	0.10	0.09	0.73	0.56	0.39
Na2O	0.11	0.42	0.42	0.44	0.44	0.46	0.79	0.43	0.47	1.13	0.54	0.65
K2O	0.98	1.85	1.83	1.78	1.62	1.82	2.34	1.76	1.99	1.98	1.75	1.90
Fe2O3	2.22	3.07	2.91	2.78	3.07	3.11	4.34	4.72	5.61	4.31	5.52	4.15
TiO2	0.24	0.47	0.43	0.27	0.38	0.34	0.70	0.35	0.56	0.61	0.91	0.53
MnO	0.03	0.04	0.03	0.03	0.03	0.35	0.02	0.03	0.07	0.07	0.13	0.08
P2O5	0.03	0.03	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.13	0.09	0.05
LOI	1.75	2.64	2.31	1.83	1.87	2.05	3.76	2.36	3.54	2.47	3.43	3.19
Total	98.66	98.98	98.89	99.02	99.31	98.78	97.91	98.84	98.15	98.28	98.97	98.74

**Sample 1* (Chittagong Sholoshohor Rail station), *2-6* (Chittagong Rail station), *10* (Kelatali section, Cox's Bazar), *11-12* (Dupi Hill section, Jaintiapur, Sylhet).

Appendix 3.2 "Whole rock" chemical composition of the Madhupur Clay sediments from various places (After Islam, 1996; Islam, 1976)

Wt%	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9**	*10**
SiO2	80.70	80.97	88.75	87.36	88.31	83.19	89.61	74.43	64.0	62.72
Al2O3	10.31	10.43	6.67	6.40	7.12	10.14	6.45	13.28	17.7	17.80
MgO	0.32	0.32	0.14	0.15	0.15	0.28	0.15	0.36	1.30	1.20
CaO	0.28	0.25	0.12	0.14	0.22	0.46	0.13	0.33	1.54	1.12
Na2O	0.27	0.28	0.31	0.34	0.50	1.05	0.28	0.44	0.68	0.98
K2O	1.63	1.67	1.53	1.56	1.77	2.70	1.52	1.9	1.20	1.35
Fe2O3	4.29	3.98	2.49	2.28	2.00	1.63	2.05	5.88	6.39	7.40
TiO2	0.44	0.42	0.31	0.25	0.29	0.25	0.27	0.56	0.90	0.60
MnO	0.04	0.03	0.01	0.02	0.02	0.01	0.02	0.08	-----	----
P2O5	0.07	0.06	0.03	0.04	0.03	0.02	0.04	0.12	-----	-----
LOI	3.07	3.13	1.56	1.45	1.31	1.77	1.43	4.05	1.25	1.96
Total	101.42	101.54	101.92	99.99	101.72	101.50	101.95	101.52	94.96	95.13

**Sample 1-8* (Mainamati-Garurhat Section), *9-10* (Madhupur Tract, Dhaka)

*Islam (1976).

Appendix 5.1 The results of chemical analyses of BWDB monitoring wells in Dhaka city

Motijheel (St. No. 54), Dhaka city, Bangladesh.

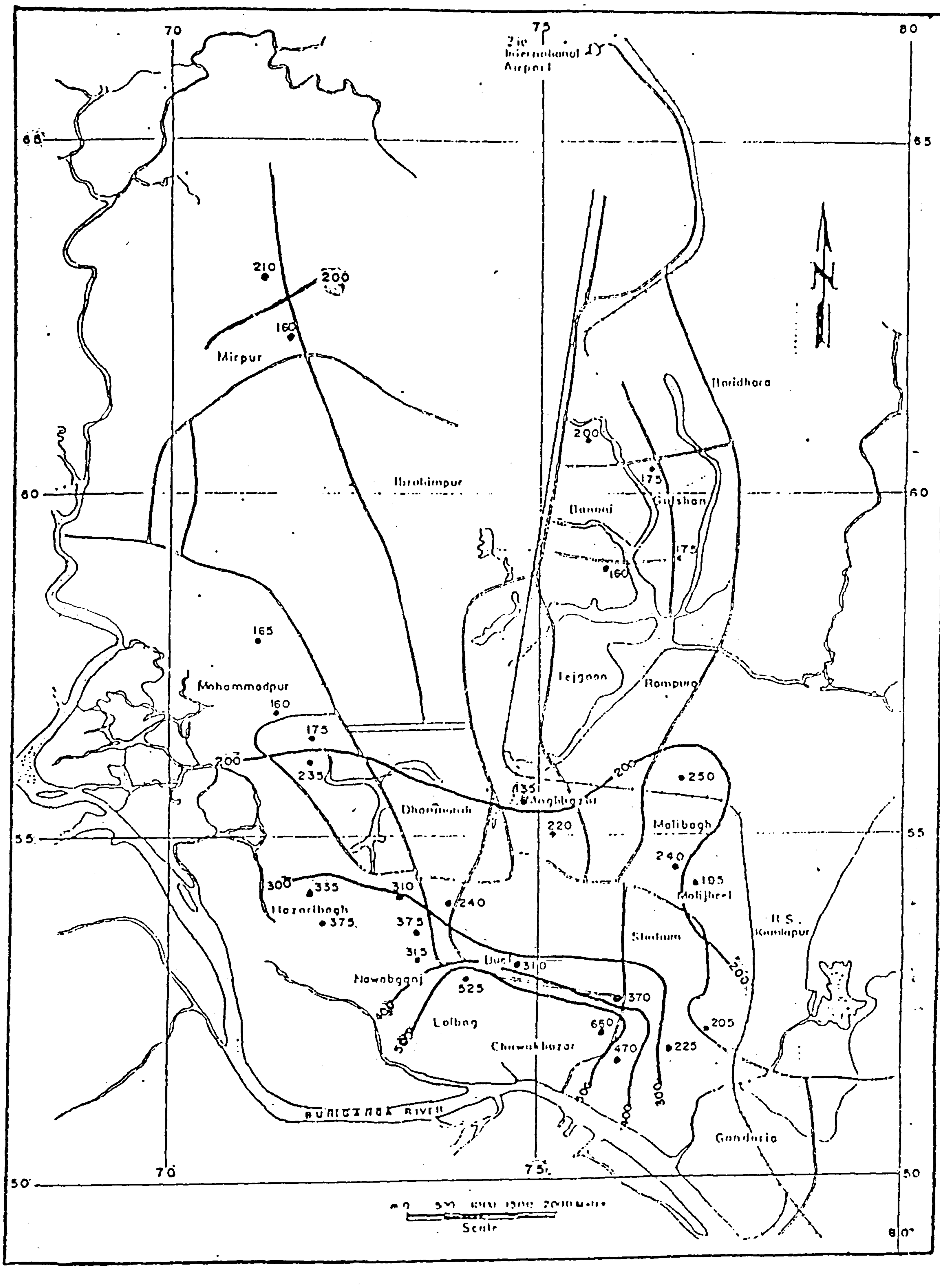
Year	pH	Ca^{2+}	Mg^{2+}	Na^{+}	Fe^{3+}	B	Cl-	HCO_3^-	SO_4^{2-}	NO_3^-	SiO_2	TDS	SAR
1994	6.61	51.20	76.80	1.88	0.06	1.00	2.90	93	2.00	2.90	0.83	233	0.23
1993	6.21	43.20	64.80	3.90	0.02	-----	6.00	66	1.00	3.70	1.28	190	-----
1990	7.00	40.00	65.00	2.00	0.03	1.00	3.00	67	3.00	3.50	-----	185	-----
1988	7.50	21.53	21.87	493.00	1.45	-----	44.77	143	24.50	-----	-----	751	-----
1985	7.70	45.65	16.17	13.55	1.40	-----	42.14	108	31.85	-----	34.50	293	-----
1984	7.00	40.00	15.00	14.00	1.00	-----	40.00	103	23.00	5.00	30.00	271	-----
1983	6.50	40.00	7.93	37.61	-----	-----	37.00	122	-----	3.00	29.50	277	1.42
1981	6.50	27.00	6.00	305.60	0.30	-----	38.00	120	-----	0.50	32.80	530	11.13
1980	6.50	29.00	9.80	48.20	-----	-----	24.50	131	-----	5.00	45.50	293	1.97
1979	9.50	17.50	11.30	56.40	2.80	-----	18.00	131	-----	5.00	37.80	280	2.58
1978	8.00	25.50	10.70	43.00	-----	-----	28.00	124	-----	4.00	32.80	268	1.50
1977	8.30	37.00	10.10	53.20	-----	-----	25.50	156	1.00	1.00	44.00	328	10.96
1976	8.10	45.00	32.00	33.00	-----	-----	102.00	483	-----	2.00	38.00	735	5.32

Mohammedpur (Station no. 102) Dhaka city, Bangladesh.

Year	p^H	Ca^{2+}	Mg^{2+}	Na^{+}	Fe^{3+}	B	Cl-	HCO_3^-	SO_4^{2-}	NO_3-	SiO_2	TDS	SAR
1994	6.12	15.20	112.80	1.04	0.22	0.00	1.60	89	0.00	0.00	0.75	221	0.11
1992	7.00	18.00	10.26	6.00		-----	20.00	65	-----	-----	-----	119	-----
1991	6.56	15.00	25.00	23.00	0.36	1.00	32.00	125	36.00	10.00	-----	267	-----
1988	6.56	17.54	12.45	61.73	5.90		14.87	120	63.70	6.00	-----	302	-----
1985	7.36	19.80	9.90	69.87	1.30	-----	17.89	140	93.10	-----	34.50	386	-----
1983	7.50	20.00	4.90	25.60	13.70	0.50	14.50	98	-----	10.00	14.40	202	1.33
1982	7.50	14.50	7.00	40.90	21.80	1.00	13.00	118	10.00	-----	23.50	250	2.21
1981	7.50	15.00	6.10	15.80	24.00	-----	12.00	104	-----	-----	10.00	187	0.87
1980	6.50	16.50	5.80	56.20	5.80	0.50	13.50	109	20.00	0.20	47.50	275	2.96
1979	7.00	18.00	9.50	69.80	5.40	-----	25.00	127	-----	3.00	58.00	316	3.38

----- Data not available

The analyses is in mg/l except SAR and pH



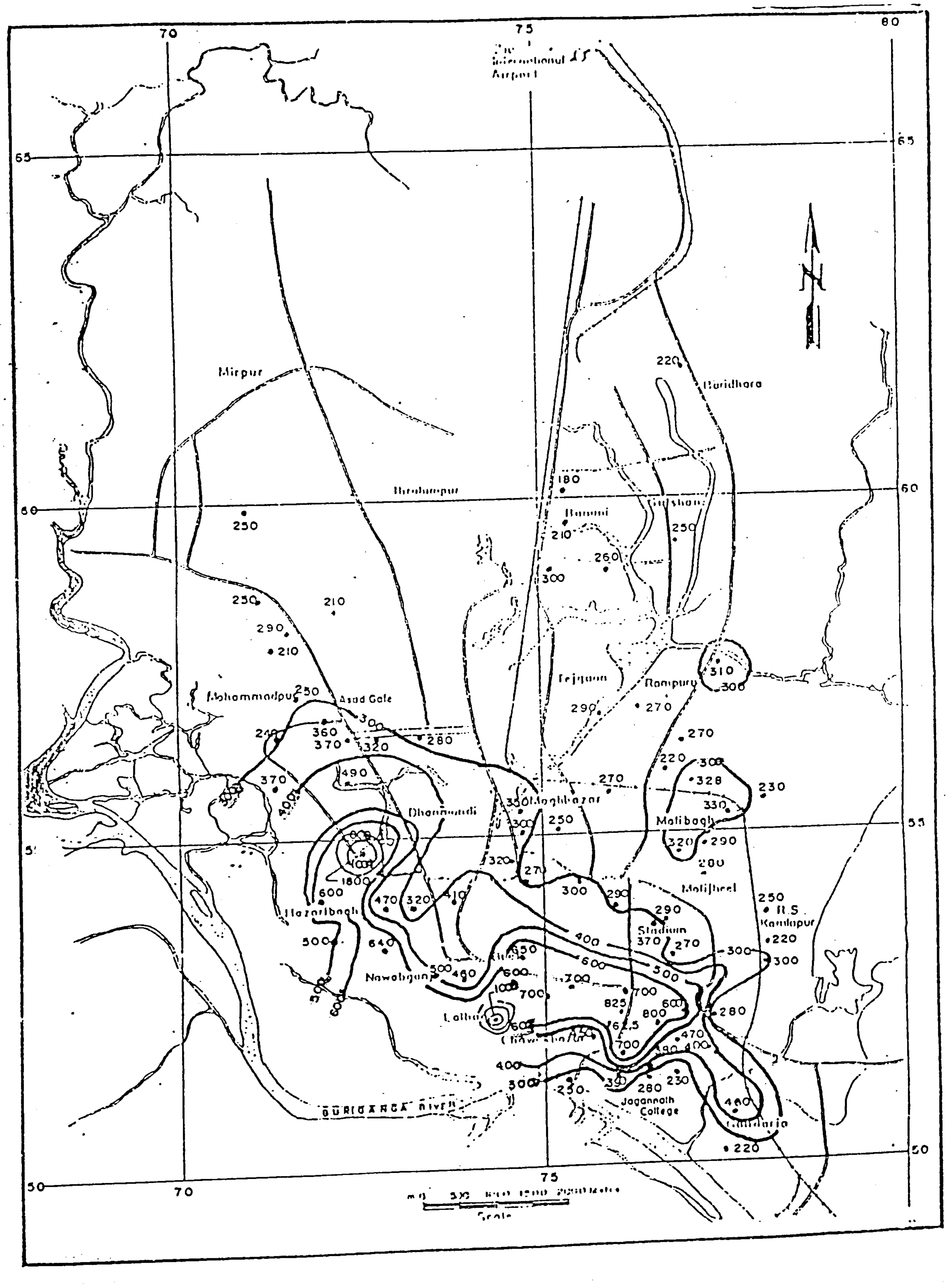
Appendix 5.2 Map of EC of groundwater, Dhaka aquifer -1966 (Welsh, 1966)

Appendix 5.3 Water sample analyses from Dhaka aquifer, mg/l (Alam, 1985)

Sample	Location	pH	Na	Ca	K	CO_3	HCO_3	Fe	NO_3	Pb	TDS
1	Khilgaon	8.1	64.0	15.7	1.93	0.40	97.0	14.5	0.87	0.02	554.0
2	Fakirapool	8.0	55.25	10.1	1.46	0.42	78.0	18.0	0.06	4.75	224.0
3	Mill Barak	7.7	50.5	30.0	1.17	0.48	98.0	16.0	0.41	0.00	298.0
4	Hazaribagh	7.5	54.5	41.0	1.19	0.50	55.0	10.5	0.76	0.02	214.0
5	Asad Gate	8.1	64.0	17.5	1.98	0.45	78.0	23.5	0.18	0.01	266.0
6	Mahakhali	7.9	52.0	19.3	1.46	0.40	77.50	17.6	0.45	0.75	510.0
7	Mirpur	7.9	61.5	26.5	1.75	0.40	84.6	16.3	0.62	0.00	281.0

Appendix 5.4 Three water sample analyses from Dhaka city, mg/l (GKW, 1990)

Sample	Location	pH	EC (uS/cm)	Na	Ca	K	Mg	Cl	SO_4	Fe	Mn
1	Hazaribagh	6.8	362	25.2	26.9	1.80	11.0	30.0	22.0	0.90	0.23
2	Armanitola	6.8	430	20.1	31.6	2.30	15.0	35.0	15.0	0.18	0.13
3	Baridhara	6.8	194	29.9	14.1	1.30	5.0	4.0	7.0	0.067	0.00



Appendix 5.5 Map of EC of groundwater, Dhaka aquifer -1989 (EPC/MMP, 1991))

Appendix 5.6 Chemical analyses of groundwater samples from the Dhaka aquifer (Ahmed, et. al., 1995)

No	Location	WASA Well	$EC_{\mu S/cm}$	pH	Tem°C	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe^{Tot}	HCO_3^-	Cl^-	F^-	NO_3^-	SO_4^{2-}
KMA-01/92	Nawabganj	205	520	6.8	25.3	31	5.75	40.37	16.87	0.3	189.1	54.4	0	12.89	16.15
KMA-02/92	Gandaria	117	290	6.9	25.1	25	2.05	18.47	7.49	0.4	143.96	15.08	0	2.76	3.71
KMA-03/92	Uttara	534	210	6.9	26	21	1.2	13.54	7.27	0.4	135.42	3.25	0.16	0.23	0.53
KMA-04/92	Mirpur 12	418	230	6.9	25.5	16	1.35	16.07	7.24	0.43	139.08	7.07	0	3.22	0
KMA-05/92	Kallyanpur	402	230	6.7	25.5	20	1.3	17.52	6.32	0.46	135.92	9.4	0	0	0
KMA-06/92	Lalmatia	306	265	6.7	27	21	1.6	20.07	8.47	0.53	142.74	17.14	0	0	6.33
KMA-07/92	Banani	518	230	6.8	25	17	1.55	14.9	3.97	0.61	142.74	3.94	0.08	0.96	0.83
KMA-08/92	Khilgaon	612	220	6.9	27	19	1.4	14.81	7.27	0.68	136.64	2.57	0	0	0
KMA-09/92	Curzon Hall	DU Well	500	6.7	27	34	2.35	37.98	17.64	0.72	200.08	41	0	25.81	24.41
KMA-11/93	Mitford	216	430	6.9	27	27.8	2.2	49.3	17.81	0	193.6	39	0	11.11	15.7
KMA-12/93	Hazaribag	210	450	6.7	27	29.1	1.5	24.3	10.2	0	157.3	37.55	0	6.64	4.01
KMA-13/93	Mirpur 1	417	160	7	27	14.5	2.5	14.8	4.22	0.07	83.6	5.72	0	0.96	0.58
KMA-15/93	Khilkhet	525	170	6.9	26	21.3	1.4	12.1	3.99	0	101.2	7.54	0	0.39	0.26
KMA-16/93	Middle Badda	517	200	7.1	26.5	21.9	1.5	16.5	5.68	0	105.6	9.4	0	0	0
KMA-17/93	Basundhara	521	165	7	26	22.3	1.2	13.2	4.89	0	97.9	5	0	0	0
KMA-18/93	Tejgaon (FDC)	501	480	6.7	26	29	2.2	57.8	13.66	0	165	51.57	0	12.57	18.26
KMA-19/93	Motijheel AGB Colony	623	280	6.8	26	25.9	1.8	30.3	10.25	0	139.7	15.7	0	3	5.5
KMA-20/93	East Madartek	614	250	6.9	27	23	1.5	15.7	6.07	0	110.25	18	0	2	5

Appendix 5.7 Nitrate analyses of groundwater samples from Dhaka ctiy (EPC/MMP, 1991)

Sample no	Name of the wells	Nitrate (mg/l)
1	Hatkhola	0.37
2	Nawabganj	0.35
3	Bangladesh Math	0.38
4	Dhanmondi-8	0.58
5	Tikkapara	0.43
6	Mirpur Section - 7	0.18
7	Shewrapara	0.35
8	Tejgaon-9	0.11
9	Gulshan - 4	0.53
10	Elephant Rd	0.70
11	Rajarbagh	0.42

Appendix 5.8 Field parameters of the samples from Keraniganj and Tongi

Sample	Location	Source/type	Depth	Temp.	pH	EC	DO_2	Alkalinity
			m	^0C		uS/cm	%	(as HCO_3 mg/l)
KHO-1	**Keraniganj**	Pumped HTW	50	22.8	6.75	440	34	260
KHO-2	**Keraniganj**	Pumped HTW	55	24.6	7.03	560	32	306
KHO-3	**Keraniganj**	Pumped HTW	60	24.9	6.54	830	33	367
KHO-4	**Keraniganj**	Pumped HTW	55	24.9	6.66	690	33	293
KHO-5	**Keraniganj**	Pumped HTW	60	24.5	6.65	590	31	271
KHO-6	**Keraniganj**	Pumped HTW	60	25.2	6.79	570	69	264
KHO-7	**Keraniganj**	Pumped HTW	50	25.1	6.56	570	22	268
KHO-8	**Keraniganj**	Pumped HTW	50	25.6	6.53	880	31	220
KHO-9	**Keraniganj**	Pumped HTW	50	25.4	6.84	680	32	360
KHO-10	**Tongi**	Pumped HTW	40	25.1	6.62	480	29	265
KHO-11	**Tongi**	Pumped HTW	35	24.9	6.5	510	28	305
KHO-12	**Tongi**	Pumped HTW	40	24.8	6.81	690	34	395
KHO-13	**Tongi**	Pumped HTW	40	25.3	6.81	470	25	265
KHO-14	**Tongi**	Pumped HTW	40	24.5	6.77	470	31	245
KHO-15	**Tongi**	Pumped HTW	35	23.3	6.67	440	32	250
KHO-16	**Tongi**	Pumped HTW	100	25	6.58	460	26	244
KHO-17	**Tongi**	Pumped HTW	30	21.9	6.4	190	40	85
KHO-18	**Tongi**	Pumped HTW	70	26	6.75	370	28	184
KHO-19	**Tongi**	Pumped HTW	35	25.1	6.77	420	28	230
KHO-20	**Tongi**	Pumped HTW	40	25.2	7.05	530	42	305
KHO-21	**Tongi**	Pumped HTW	35	25.8	6.8	430	31	225
KHO-22	**Tongi**	Pumped HTW	30	25	6.78	320	27	184
KHO-23	**Tongi**	Pumped HTW	20	26.54	6.93	660	32	295
KHO-24	**Dattapara**	Pumped HTW	30	22.5	6.43	1590	28	540
KHO-25	**Dattapara**	Pumped HTW	35	25.9	6.58	850	30	305
KHO-26	**Dattapara**	Pumped HTW	30	22.9	6.58	1230	28	305
KHO-27	**Dattapara**	Pumped HTW	40	24.4	6.76	1050	43	248
KHO-28	**Dattapara**	Pumped HTW	30	24.1	6.52	1450	34	220
KHO-29	**Dattapara**	Pumped HTW	20	25	6.44	1600	29	310
KHO-30	**Dattapara**	Pumped HTW	20	24.9	6.29	1110	30	240
KHO-31	**Dattapara**	Pumped HTW	25	24.5	6.63	1530	33	190

Appendix 5.8 Chemical analyses of samples from Keraniganj and Tongi

Sample	Cations mg/l					Anions mg/l				
	Ca^{2+}	Na^{+}	Mg^{2+}	K^{+}	Fe^{3+}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	TDS mg/l
KHO -1	53.40	19.20	2.60	13.33	0.35	260	1.20	0.00	1.28	351
KHO -2	65.30	19.60	2.80	16.21	0.11	306	4.67	0.43	0.00	415
KHO -3	96.50	27.00	3.30	22.90	2.90	367	67.57	0.11	0.00	587
KHO -4	70.50	30.00	3.20	26.39	0.17	293	61.15	13.05	0.00	497
KHO -5	58.60	29.10	3.20	19.00	0.46	271	34.55	2.60	0.00	418
KHO -6	78.50	33.70	3.40	25.03	0.27	264	59.04	48.48	0.00	512
KHO -7	54.80	30.50	3.50	17.85	0.07	268	25.22	1.18	0.00	401
KHO -8	84.50	42.00	3.40	26.05	0.22	220	95.87	70.49	0.00	543
KHO -9	84.20	16.50	3.20	24.94	0.25	360	26.92	0.12	0.00	516
KHO -10	32.50	34.50	1.40	20.33	0.77	265	3.05	0.00	0.00	358
KHO -11	35.60	44.70	1.60	21.52	3.84	305	3.39	3.64	0.09	419
KHO -12	58.50	58.10	1.30	23.72	0.53	395	9.67	0.20	0.00	547
KHO -13	36.50	31.50	1.30	19.69	0.26	265	5.25	0.00	0.00	360
KHO -14	32.50	28.30	1.80	20.13	0.25	245	7.47	0.44	0.00	336
KHO -15	32.50	29.30	1.80	18.87	0.80	250	2.67	2.98	0.65	340
KHO -16	35.50	30.50	2.00	17.24	0.01	244	4.70	0.39	0.23	335
KHO -17	11.10	17.50	0.50	4.94	2.44	85	9.50	2.76	0.00	134
KHO -18	23.50	30.50	1.50	10.95	0.99	184	3.67	0.00	0.00	255
KHO -19	27.50	34.60	1.30	13.42	0.51	230	2.50	0.60	0.16	311
KHO -20	33.50	46.70	1.40	17.85	0.39	305	4.23	0.32	0.00	409
KHO -21	29.60	30.40	1.70	15.62	0.25	225	3.47	0.24	0.00	306
KHO -22	20.50	27.80	1.30	10.92	1.02	184	3.10	0.37	0.00	249
KHO -23	55.60	44.50	1.40	20.58	0.18	295	30.77	9.37	0.00	457
KHO -24	145.60	138.70	3.20	46.37	11.06	540	305.17	3.71	0.00	849
KHO -25	78.60	53.80	2.10	25.80	3.24	305	105.44	2.86	0.00	413
KHO -26	125.60	60.50	2.50	44.57	3.92	305	247.20	3.39	0.90	556
KHO -27	112.30	55.20	1.70	32.68	1.13	248	232.47	57.54	1.72	540
KHO -28	137.50	95.60	1.60	38.87	1.58	220	279.84	67.13	6.68	849
KHO -29	164.50	100.60	1.80	46.16	0.55	310	340.62	56.63	1.21	1022
KHO -30	108.60	53.80	2.00	39.47	0.30	240	217.31	12.43	1.36	675
KHO -31	170.10	66.40	3.70	52.16	1.56	190	357.49	58.78	4.52	905

Appendix 5.9 An example field sheet (used for each sample in the field)

WATER SAMPLING RECORD

Department of Geological Sciences, UCL, Gower Street, London WC1E 6BT.

COLLECTOR..

DATE SAMPLED........................SAMPLE No..

Map number..Map reference..............................

Name of source..
Location relative to prominent features ....
....
....
(Draw a map on the reverse of this sheet)

Address for contact / owner ....
....
....
....
....
....
Tel/Fax No..

Producing Formation..
Depth of source...
Screened at...

Water level.......................... Flow/Pumping rate..

Temperature.......................... Colour........................ Turbidity.........................

pH..................................... E.C.(μS cm^{-1} @ 25°C)...

DO..................................... Alkalinity (Hach units)......................................
.... Alkalinity (mM. H^{+})..

Main Use(s) Irrigation Stock Industrial Domestic Leisure Other.........

REMARKS..
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Appendix 5.10 Field-test results of samples from the Dhaka aquifer

Sample	Location	Source/type	Depth	Temp.	pH	EC	DO_2	Alkalinity
			m	^0C		uS/cm	%	(as HCO_3 mg/l)
KH-1	Hazaribagh-4	Pumped DTW	124.5	26.8	6.02	510	27*	232
KH-2	Hazaribagh-5	Pumped DTW	148.5	28.1	6.14	440	8	179
KH-3	Hazaribagh-3	Pumped DTW	142.5	27.3	6.22	600	40	216**
KH-4	Rayer Bazar	Pumped DTW	152.0	27.2	6.22	370	15*	161
KH-5	*D K School (R.Bazar)*	*Pumped HTW*	*40.2*	*27.1*	*6.07*	*1050*	*10**	*218*
KH-6	Sultanganj (R.Bazar)	Pumped DTW	133.8	26.2	6.40	360	11	166**
KH-7	Peel Khana-2	Pumped DTW	121.9	27.1	6.30	420	36*	194
KH-8	Bangladesh Math	Pumped DTW	135.7	27.2	5.93	590	28	237
KH-9	Fulbaria OHT	Pumped DTW	154.7	27.2	6.68	650	45*	244
KH-10	Dhaka Water Works	Pumped DTW	129.1	33.8	6.40	830	50	285
KH-11	Islambagh	Pumped DTW	N/A	27.5	6.40	350	10*	155
KH-12	Dholaikhal	Pumped DTW	N/A	27.4	6.05	390	29	150
KH-13	Gandaria DIT	Pumped DTW	154.0	26.7	6.34	360	6*	126
KH-14	I G Gate	Pumped DTW	N/A	28.3	6.36	200	6	104
KH-15	Saidabad	Pumped DTW	152.0	27.4	6.02	550	5*	230**
KH-16	Jatrabari Chowrasta	Pumped DTW	152.4	27.3	6.48	200	12*	146
KH-17	*Kutubkhali*	*Pumped HTW*	*50.0*	*26.8*	*6.84*	*710*	*4*	*369*
KH-18	Kazla	Pumped DTW	175.0	27.2	6.52	190	8*	136
KH-19	Jatrabari WAPDA col	Pumped DTW	166.8	27.7	6.73	300	11*	140
KH-20	Gopibagh	Pumped DTW	178.0	27.1	6.35	420	30	189
KH-21	*Mugdapara*	*Pumped HTW*	*53.0*	*27.9*	*5.77*	*380*	*31**	*112*
KH-22	Maniknagar	Pumped DTW	133.5	26.8	6.62	310	25	154**
KH-23	Mugdapara	Pumped DTW	165.5	27.5	6.55	250	58	143
KH-24	Manda	Pumped DTW	N/A	30.1	6.79	300	7*	176
KH-25	Goran-1	Pumped DTW	180.7	27.6	6.53	190	11	150
KH-26	Madartek Project	Pumped DTW	N/A	31.6	6.72	180	5*	143
KH-27	Madartek	Pumped DTW	169.8	27.7	6.72	180	15	140
KH-28	Bashaboo-2	Pumped DTW	134.0	26.4	6.32	340	8*	171**
KH-29	Circuit House	Pumped DTW	N/A	27.2	5.86	210	16*	99
KH-30	Bijoynagar	Pumped DTW	131.1	27.1	6.60	310	35	150**
KH-31	Tejgaon Industrial Area	Pumped DTW	116.0	27.1	6.02	260	25*	95
KH-32	Tejgaon -9	Pumped DTW	144.8	26.9	5.90	280	30	102
KH-33	Niketon	Pumped DTW	N/A	27.1	6.48	180	8*	121
KH-34	Nakhalpara	Pumped DTW	132.6	27.3	6.32	150	65	110
KH-35	Moghbazar Red Cresent	Pumped DTW	167.0	26.8	6.70	250	50*	126
KH-36	Madhubag	Pumped DTW	172.0	25.8	6.50	190	20*	143**
KH-37	Khilgaon (new)	Pumped DTW	N/A	26.7	6.62	200	24	156
KH-38	Mogbazar Wirless Col	Pumped DTW	159.3	27.1	6.41	400	26*	196
KH-39	Rajarbag	Pumped DTW	169.0	27.8	6.65	240	52	152
KH-40	Pangu Hospital	Pumped DTW	155.0	27.5	6.03	170	15*	112
KH-41	Kallayanpur	Pumped DTW	125.0	27.2	6.06	240	18	140
KH-42	Pererbag	Pumped DTW	150.0	27.1	6.50	250	14*	156**
KH-43	Shamoli	Pumped DTW	138.3	26.4	6.22	230	15*	148
KH-44	Md.pur Pisic.H/S	Pumped DTW	140.8	26.7	6.35	210	17	180
KH-45	Salimullah Rd (Md.pur)	Pumped DTW	137.0	27.5	6.33	170	20*	145
KH-46	Asad Gate (Md.pur)	Pumped DTW	114.8	29.1	6.00	240	37	115
KH-47	Rampura	Pumped DTW	143.6	26.5	6.14	230	24*	163
KH-48	Banosree H/S	Pumped DTW	N/A	25.7	6.18	170	20	118
KH-49	Ulan (Rampura)	Pumped DTW	172.5	25.8	6.18	240	11	187**
KH-50	Shahjadpur	Pumped DTW	175.3	27.7	6.42	140	15*	122
KH-51	Nurerchala	Pumped DTW	178.0	29.4	6.72	190	17*	124
KH-52	Nayanagar	Pumped DTW	165.5	27.3	6.47	180	18*	124
KH-53	Gulshan-4	Pumped DTW	135.9	26.6	6.27	190	50*	102
KH-54	Banani-5	Pumped DTW	175.3	31.2	7.16	310	66	159
KH-55	Banani-4	Pumped DTW	135.5	26.7	6.00	160	60*	92**
KH-56	Mohakhali T. B. Gate	Pumped DTW	128.0	26.7	6.23	190	60	113

Appendix 5.10 Sample description and field test results from the Dhaka aquifer

Sample	Location	Source/type	Depth	Temp.	p^H	EC	DO_2	Alkalinity
			m	°C		uS/cm	%	(as HCO_3 mg/l)
KH-57	New Eskaton	Pumped DTW	163.0	27.3	5.97	360	50*	145
KH-58	Bakshibazar	Pumped DTW	137.3	28.2	6.68	530	45	287**
KH-59	New Elephant Rd.	Pumped DTW	134.0	27.3	6.20	260	30*	164
KH-60	Green Rd-4	Pumped DTW	128.6	26.1	6.40	310	30*	159
KH-61	Dhanmandi-4	Pumped DTW	117.3	27.1	6.30	430	70	155
KH-62	Lalmatia	Pumped DTW	125.6	27.2	6.50	200	22*	141**
KH-63	Jhikatala	Pumped DTW	114.4	26.7	6.90	1250	10*	187
KH-64	PWD S/Q (R.Bazar)	Pumped DTW	150.0	27.1	6.10	420	26*	176
KH-65	Bangla College	Pumped DTW	97.6	27.3	5.94	150	15	121
KH-66	Gudaraghat (Mirpur)	Pumped DTW	109.8	27.6	5.70	150	18*	76
KH-67	Golartake	Pumped DTW	N/A	31.9	6.40	170	8	113**
KH-68	BIBM Mirpur	Pumped DTW	167.7	26.6	5.90	150	50*	71
KH-69	Rupnagar	Pumped DTW	107.1	26.3	6.15	150	20	117
KH-70	Duyaripara	Pumped DTW	N/A	27.2	6.15	145	28*	94
KH-71	Mirpur (Block-D)	Pumped DTW	N/A	32.5	6.40	150	30	113
KH-72	Pallabi	Pumped DTW	169.8	27.2	6.03	160	17*	100
KH-73	Mirpur (Sec.11)	Pumped DTW	127.8	27.1	6.16	170	25	105**
KH-74	Mirpur (Sec.10)	Pumped DTW	138.0	26.8	6.50	180	45*	77
KH-75	*Swarighat*	*River Buriganga*	*surface*	*28.1*	*7.60*	*310*	*50*	*169*
KH-76	*Zinzirabazar*	*Pumped HTW*	*45.0*	*28.1*	*6.75*	*410*	*10**	*298*
KH-77	*Nekrulbagh*	*Pumped STW*	*75.0*	*26.9*	*6.36*	*320*	*12**	*265*
KH-78	*Tongi*	*Tongi Khal*	*surface*	*25.9*	*6.62*	*600*	*60*	*257*
KH-79	*Abdullahpur (Tongi)*	*Pumped HTW*	*50.0*	*26.1*	*6.30*	*200*	*30**	*142*
KH-80	Uttara-3	Pumped DTW	172.5	29.4	6.50	190	5*	136
KH-81	Uttara-2	Pumped DTW	164.0	27.1	6.56	210	3	132
KH-82	Khilkhet Bazar	Pumped DTW	167.0	27.9	7.22	150	12*	105
KH-83	Namapara	Pumped DTW	164.2	28.1	7.01	180	55*	120
KH-84	Kawlar-1	Pumped DTW	153.3	28.1	6.50	160	5*	113
KH-85	Kalachandpur	Pumped DTW	176.8	29.1	6.69	180	4	113**
KH-86	Baridhara	Pumped DTW	171.0	27.9	6.47	210	55*	115
KH-87	Basundhara H/S	Pumped DTW	164.3	27.6	6.73	180	4	124
KH-88	J.N.College	Pumped DTW	179.0	28.1	5.82	550	35*	226**
KH-89	Dhaka Jute Mills	Pumped DTW	N/A	27.2	6.30	360	30	196
KH-90	Nilkhet Women Hos	Pumped DTW	145.0	27.3	6.01	420	13*	151
KH-91	Azimpur OHT	Pumped DTW	153.3	27.8	6.76	500	15*	196
KH-92	Nawabganj	Pumped DTW	134.7	27.9	6.54	440	14	189
KHF-1	Agamachi Lane	Pumped DTW	144.2	28.3	6.43	750	52*	221
KHF-2	Armanitola	Pumped DTW	135.6	27.4	6.13	440	60	197
KHF-3	Mitford Hospital	Pumped DTW	180.0	27.4	6.33	430	17*	185
KHF-4	Dayaganj	Pumped DTW	125.0	27.7	6.76	400	59	154
KHF-5	Dhopkhola Math	Pumped DTW	154.0	27.8	6.48	270	50*	110
KHF-6	Jurain	Pumped DTW	165.1	27.3	6.95	200	9*	117
KHF-7	Paterbagh	Pumped DTW	156.7	27.4	6.64	230	4	129
KHF-8	Ahmedbag	Pumped DTW	182.0	28.5	6.59	240	41	106
KHF-9	Goran-2	Pumped DTW	N/A	27.4	6.30	190	32*	104
KHF-10	Nandipara	Pumped DTW	N/A	27.6	6.72	200	68	96
KHF-11	Segunbagicha	Pumped DTW	N/A	27.3	5.94	260	55*	106
KHF-12	Khilgaon-5	Pumped DTW	155.3	26.2	6.46	230	60	99
KHF-13	Banani-3	Pumped DTW	135.5	28.7	6.03	180	56*	74
KHF-14	DOHS (Mohakhali)	Pumped DTW	161.0	27.5	6.02	200	60	96
KHF-15	DOHS (Mohakhali) New	Pumped DTW	142.7	26.9	6.18	220	61	102
KHF-16	Mirpur Sec.10	Pumped DTW	121.3	26.8	6.18	160	45*	65
KHF-17	Nandail Bazar	*Pumped HTW*	50.0	26.9	6.36	320	19*	176
KHS 1	Agargaon slum	Pumped HTW	60	26.2	6.50	170	20*	66
KHS 2	Agargaon slum	Pumped HTW	55	26.1	6.40	550	35	98
KHS 3	Agargaon slum	Pumped HTW	52	26.1	6.50	620	35*	100

Appendix 5.10 Sample description and field test results from the Dhaka aquifer

Sample	Location	Source/type	Depth	Temp.	P^H	EC	DO_2	Alkalinity
			m	^0C		uS/cm	%	(as HCO_3 mg/l)
KHS 4	T T Para slum	Pumped HTW	50	26.6	6.55	460	22*	154
KHS 5	City slum Dhalpur	Pumped HTW	60	25.9	6.94	580	25*	186
KHS 6	City slum Dhalpur	Pumped HTW	90	25.9	6.65	250	18	142
KHS 7	Jatrabari	Pumped HTW	60	27	6.60	1550	20*	603
KHS 8	Sanir Akhra	Pumped HTW	75	26	6.97	510	28*	234
KHS 9	Sonatake	Pumped HTW	70	29	6.85	650	24*	298
KHS 10	Hrishikesh Das Rd	Pumped HTW	85	26.7	6.48	820	23*	256
KHS 11	Suklal Das Lane	Pumped HTW	80	26.5	6.56	620	23	256
KHS 12	Sham Bazar	Pumped HTW	75	26.4	6.95	780	20*	356
KHS 13	kamrangir char	Pumped HTW	75	25.8	6.68	240	20*	109
KHS 14	kamrangir char	Pumped HTW	70	26.3	6.75	300	20*	188
KHS 15	kamrangir char	Pumped HTW	80	25.8	7.10	780	22*	427
KHS 16	Rajnaran Dhar Rd	Pumped HTW	65	24.2	6.98	720	16*	342
KHS 17	Hazaribagh	Pumped HTW	60	25.6	6.65	440	32	195
KHS 18	Hazaribagh	Pumped HTW	55	25.4	6.35	950	33*	220
KHS 19	Kazal Tak	Pumped HTW	50	22.5	7.00	280	35*	130
KHS 20	Bhasantake	Pumped HTW	35	25.4	6.59	480	35	220
KHS 21	Mirpur 12	Pumped HTW	40	26.1	6.20	520	27*	134

*** The sites where flow cell was used**

**** The samples where alkalinity measurements were repeated**

KHF-Only well head measurements were taken (no sample)

Appendix 5.11 Chemical analyses (major components) of groundwater samples

Sample	Cations mg/l					Anions mg/l				
	Na^+	Ca^{2+}	Mg^{2+}	K^+	Tot. Fe	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	TDS mg/l
KH-1	39.8	48.3	18.6	2.5	-----	232	55.3	17.7	1.1	416
KH-2	31.3	45.4	15.8	3.0	0.25	179	56.5	13.8	2.7	347
KH-3	56.8	46.9	15.5	2.9	0.05	216	63.4	13.8	3.5	418
KH-4	26.9	34.3	11.7	2.3	-----	161	26.7	7.8	1.8	273
KH-5	48.5	137.3	37.4	5.9	0.39	228	255.9	5.9	0.7	719
KH-6	28.5	35.8	14.0	1.7	0.04	166	36.4	7.1	0.0	289
KH-7	34.1	40.0	13.4	14.3	-----	194	31.6	20.5	3.5	351
KH-8	41.9	57.9	23.5	3.2	-----	237	53.5	23.2	16.1	456
KH-9	52.3	67.1	22.1	3.1	-----	244	67.7	32.5	20.7	509
KH-10	80.6	66.7	21.9	7.0	-----	285	109.1	11.0	2.6	584
KH-11	22.3	42.2	12.9	2.4	0.23	155	42.8	10.4	1.0	290
KH-12	31.5	43.2	14.1	2.4	-----	150	40.5	24.6	11.9	318
KH-13	31.2	35.6	12.0	2.0	-----	126	55.6	14.4	0.9	278
KH-14	22.6	17.1	6.6	1.5	-----	104	17.2	5.9	1.2	176
KH-15	39.0	58.1	21.8	2.3	-----	230	56.2	27.8	1.3	437
KH-16	23.3	17.9	6.6	1.5	0.95	146	5.0	1.6	0.4	203
KH-17	60.9	83.3	28.7	2.1	1.35	369	64.1	16.1	0.2	625
KH-18	23.6	18.3	6.9	1.6	0.37	136	5.3	9.7	0.3	202
KH-19	25.9	17.8	7.0	1.6	-----	140	5.2	0.3	0.2	198
KH-20	33.1	46.3	17.8	2.1	-----	189	44.6	19.7	1.2	354
KH-21	32.1	44.6	15.6	1.8	0.83	112	68.6	31.1	15.6	323
KH-22	24.0	26.4	11.3	1.6	-----	154	14.6	6.4	0.6	239
KH-23	22.3	17.9	6.6	1.8	-----	143	5.1	1.8	0.5	199
KH-24	26.2	29.5	11.0	1.7	0.05	176	10.5	9.8	0.5	265
KH-25	22.9	18.9	6.1	2.0	-----	150	4.9	2.2	0.3	207
KH-26	22.1	17.1	7.5	1.9	-----	143	6.1	1.9	0.4	199
KH-27	24.6	16.4	6.3	1.7	-----	140	4.1	0.9	0.3	195
KH-28	31.1	37.2	11.0	2.6	-----	171	28.7	14.8	0.2	296
KH-29	17.9	18.7	7.0	2.3	-----	99	16.7	6.3	0.5	168
KH-30	22.9	52.0	12.2	2.3	-----	150	44.5	17.4	10.3	312
KH-31	25.9	28.5	9.2	2.9	0.01	95	37.5	14.0	18.9	231
KH-32	23.4	26.9	9.3	3.6	0.12	102	31.2	15.0	16.9	229
KH-33	21.0	22.0	9.6	2.2	0.16	121	19.5	3.1	2.3	200
KH-34	18.3	20.3	7.2	1.9	-----	110	15.9	5.7	3.5	183
KH-35	19.9	24.3	11.0	2.2	-----	126	20.6	5.0	3.7	213
KH-36	29.3	20.5	11.9	2.0	-----	143	18.8	12.9	0.9	239
KH-37	21.5	19.2	7.9	2.2	0.43	156	4.5	0.9	0.3	213
KH-38	27.4	42.3	16.5	2.6	-----	196	35.1	6.4	1.0	328
KH-39	24.9	34.9	14.4	2.2	-----	152	36.3	7.2	3.4	276
KH-40	17.9	17.3	6.5	2.1	-----	112	12.6	3.1	0.2	172
KH-41	22.5	25.1	7.7	2.0	-----	140	13.0	1.6	0.0	212
KH-42	24.1	25.2	9.2	2.0	-----	156	12.1	2.0	0.0	231
KH-43	20.1	24.3	7.9	2.1	-----	148	12.1	4.0	0.0	218
KH-44	22.6	31.4	10.7	2.2	-----	180	10.1	2.6	0.0	259
KH-45	19.9	22.8	8.3	2.4	-----	145	10.2	2.8	0.0	212
KH-46	20.3	22.6	7.5	2.6	-----	115	26.1	6.0	9.3	209
KH-47	28.4	28.5	10.7	2.2	-----	163	20.9	4.4	0.3	259
KH-48	29.9	17.8	7.2	1.8	-----	118	6.5	0.6	0.3	182
KH-49	58.4	14.8	5.1	1.8	-----	187	18.7	0.5	0.0	286
KH-50	20.1	18.0	5.4	1.9	0.20	122	8.1	0.7	0.0	177
KH-51	21.0	17.4	5.8	2.1	2.68	124	5.3	0.1	0.0	178
KH-52	22.1	17.2	5.2	1.9	0.02	124	2.9	0.4	0.3	174
KH-53	16.6	18.9	6.7	1.9	-----	102	13.9	1.4	9.4	171
KH-54	31.1	22.3	7.7	3.9	0.09	159	10.0	2.0	4.0	241
KH-55	14.1	16.2	4.9	2.4	-----	92	10.1	0.7	13.3	154
KH-56	19.0	18.7	6.2	2.3	-----	113	8.9	2.8	2.9	174

Appendix 5.11 Chemical analyses (major components) of groundwater samples

Sample	Na^+	Ca^{2+}	Mg^{2+}	K^+	Fe^{3+}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	TDS mg/l
KH-57	26.8	37.1	11.7	3.5	0.04	145	40.3	18.1	11.8	295
KH-58	46.4	80.8	31.6	3.2	-----	287	63.0	31.8	24.0	568
KH-59	23.4	33.3	14.6	2.5	-----	164	36.5	16.5	11.6	302
KH-60	23.9	32.5	13.3	2.3	0.10	159	22.9	7.4	3.4	265
KH-61	32.4	42.9	16.3	2.1	-----	155	65.9	12.3	6.9	333
KH-62	20.9	26.9	9.5	1.9	0.02	141	19.6	5.0	0.1	225
KH-63	148.7	85.3	30.4	3.9	-----	187	240.5	88.1	26.4	810
KH-64	31.6	44.8	16.6	2.4	-----	176	44.6	17.2	11.4	*345*
KH-65	23.7	33.9	10.3	1.9	-----	121	16.7	2.7	4.2	214
KH-66	*14.0*	15.8	*4.2*	2.7	-----	76	10.0	0.6	5.7	129
KH-67	17.0	17.1	6.3	1.6	0.09	113	7.8	0.5	2.8	166
KH-68	14.2	14.6	4.9	2.4	0.17	*71*	21.0	0.1	4.9	134
KH-69	16.2	19.0	7.4	1.6	-----	117	8.1	0.2	0.0	169
KH-70	16.9	19.0	7.0	1.7	-----	94	23.4	0.8	0.0	162
KH-71	20.5	21.8	7.1	1.6	-----	113	7.2	0.3	4.2	175
KH-72	15.9	17.2	6.5	1.6	-----	100	14.0	0.2	0.2	156
KH-73	15.6	19.6	7.0	2.0	0.17	105	13.7	0.0	0.2	164
KH-74	17.1	21.5	8.4	1.8	-----	77	30.0	12.4	13.5	182
KH-75	34.4	31.5	13.1	7.2	-----	169	31.0	13.0	14.0	313
KH-76	22.6	66.5	22.9	7.5	8.22	298	33.2	0.2	8.2	467
KH-77	17.9	59.8	16.6	4.1	12.60	265	5.6	13.6	0.2	396
KH-78	88.3	41.0	12.0	12.0	0.02	257	67.6	18.8	12.0	509
KH-79	31.0	24.8	7.8	1.7	1.69	142	5.9	0.9	0.7	217
KH-80	23.3	19.3	6.8	1.4	0.40	136	5.1	*0.0*	0.0	192
KH-81	23.3	20.9	9.0	1.6	-----	132	5.3	0.0	0.0	192
KH-82	19.1	12.4	4.4	1.6	-----	105	2.8	0.1	0.2	146
KH-83	21.5	15.9	5.7	1.5	-----	120	4.5	0.5	0.2	169
KH-84	19.2	14.6	6.4	1.1	-----	113	3.6	0.8	2.9	161
KH-85	21.0	15.8	5.5	1.4	-----	113	7.8	0.3	0.0	165
KH-86	21.5	18.8	5.7	1.5	-----	115	15.6	0.8	0.6	179
KH-87	22.3	14.4	5.1	1.4	0.12	124	*2.6*	0.2	0.0	170
KH-88	42.1	55.0	14.6	5.5	-----	226	41.7	17.7	12.7	415
KH-89	31.2	34.7	13.6	1.8	0.52	196	18.8	11.4	0.0	308
KH-90	29.6	46.8	16.5	2.3	-----	151	49.8	32.1	21.2	349
KH-91	44.3	53.8	17.1	5.7	-----	196	55.0	34.9	18.5	426
KH-92	27.4	46.7	16.1	4.6	-----	189	37.1	20.3	2.2	343
KHS 1	9.6	12.5	1.8	4.5	0.16	66	7.89	1.3	3.5	104
KHS 2	42.5	30.5	3.4	15.8	0.05	98	76.9	14.2	19.8	301
KHS 3	52.3	29.6	3.6	18.7	0.01	100	108.9	1.4	23.7	338
KHS 4	38.6	24.5	2.2	18.2	4.07	154	39.4	29.3	0.0	310
KHS 5	55.8	26.5	4.6	31.9	2.32	186	55.9	66.1	3.6	432
KHS 6	20.3	21.2	1.6	9.4	0.72	142	10.5	0.5	0.5	206
KHS 7	158.0	83.0	6.1	62.9	1.88	603	200.0	12.4	0.2	1127
KHS 8	50.5	36.3	2.4	20.5	0.79	234	34.5	27.1	0.7	407
KHS 9	60.2	49.0	2.0	20.1	5.39	298	45.5	26.0	0.3	506
KHS 10	44.8	55.0	64.1	21.7	0.28	256	74.4	32.5	36.3	585
KHS 11	50.5	43.2	10.7	22.0	0.54	256	42.0	20.4	4.8	450
KHS 12	75.8	45.7	37.6	23.8	1.59	356	57.1	14.6	7.3	620
KHS 13	21.5	14.5	2.6	8.1	0.04	109	18.6	2.6	3.5	174
KHS 14	32.2	24.0	2.2	9.3	0.63	188	6.3	2.3	4.6	265
KHS 15	118.1	17.6	3.8	22.8	6.48	427	16.9	20.5	2.6	633
KHS 16	75.6	30.0	4.6	31.9	2.32	342	50.4	14.6	3.6	551
KHS 17	43.5	22.4	2.1	15.5	0.08	195	31.8	0.3	6.3	311
KHS 18	78.6	46.2	3.3	30.8	0.16	220	116.7	78.2	5.3	573

Appendix 5.12 Result of chemical analysis with ionic balance check

Sample	Cations meq/l					Anions meq/l						
	Na^+	Ca^{2+}	Mg^{2+}	K^+	Tot^+	HCO_3^-	Cl^-	SO_4^{2-}	$NO3^-$	Tot^-	TDI	Balance %
KH-1	1.73	2.41	1.53	0.06	5.73	3.81	1.56	0.37	0.02	5.75	11.49	-0.35
KH-2	1.36	2.27	1.30	0.08	5.00	2.93	1.59	0.29	0.04	4.85	9.85	3.05
KH-3	2.47	2.34	1.27	0.07	6.16	3.53	1.79	0.29	0.06	5.67	11.82	8.29
KH-4	1.17	1.71	0.97	0.06	3.91	2.64	0.75	0.16	0.03	3.59	7.49	8.54
KH-5	2.11	6.85	3.08	0.15	12.19	3.72	7.22	0.12	0.01	11.97	23.26	1.89
KH-6	1.24	1.79	1.15	0.04	4.22	2.72	1.03	0.15	0.00	3.89	8.12	8.13
KH-7	1.48	2.00	1.10	0.37	4.95	3.17	0.89	0.43	0.06	4.55	9.49	8.43
KH-8	1.82	2.89	1.93	0.08	6.73	3.88	1.51	0.48	0.26	6.13	12.86	9.33
KH-9	2.27	3.35	1.81	0.08	7.52	3.99	1.91	0.68	0.33	6.91	14.43	8.45
KH-10	3.50	3.33	1.81	0.18	8.82	4.66	3.08	0.23	0.04	8.01	16.83	9.63
KH-11	0.97	2.11	1.06	0.06	4.20	2.55	1.21	0.22	0.02	3.99	8.19	5.13
KH-12	1.37	2.16	1.16	0.06	4.74	2.46	1.14	0.51	0.19	4.31	9.05	9.50
KH-13	1.36	1.78	0.98	0.05	4.17	2.07	1.57	0.30	0.02	3.95	8.12	5.42
KH-14	0.98	0.85	0.54	0.04	2.42	1.70	0.49	0.12	0.02	2.33	4.74	3.80
KH-15	1.70	2.90	1.79	0.06	6.44	3.77	1.59	0.58	0.02	5.96	12.4	7.74
KH-16	1.01	0.89	0.54	0.04	2.49	2.39	0.14	0.03	0.01	2.57	5.06	-3.16
KH-17	2.65	4.16	2.36	0.05	9.22	6.04	1.81	0.33	0.00	8.18	17.4	11.95
KH-18	1.03	0.91	0.57	0.04	2.55	2.22	0.15	0.20	0.00	2.58	5.13	-1.17
KH-19	1.13	0.89	0.57	0.04	2.63	2.29	0.15	0.01	0.00	2.44	5.07	7.50
KH-20	1.44	2.31	1.46	0.05	5.26	3.10	1.26	0.41	0.02	4.79	10.05	9.35
KH-21	1.40	2.23	1.28	0.05	4.95	1.84	1.94	0.65	0.25	4.68	9.63	5.61
KH-22	1.04	1.32	0.93	0.04	3.33	2.53	0.41	0.13	0.01	3.08	6.41	7.80
KH-23	0.97	0.89	0.54	0.05	2.45	2.35	0.14	0.04	0.01	2.54	4.99	-3.61
KH-24	1.14	1.47	0.90	0.04	3.56	2.88	0.29	0.20	0.01	3.38	6.94	5.19
KH-25	1.00	0.94	0.50	0.05	2.49	2.45	0.14	0.05	0.00	2.64	5.14	-5.84
KH-26	0.96	0.85	0.62	0.05	2.48	2.34	0.17	0.04	0.01	2.55	5.03	-2.78
KH-27	1.07	0.82	0.52	0.04	2.45	2.30	0.12	0.02	0.00	2.44	4.89	0.41
KH-28	1.35	1.86	0.90	0.07	4.18	2.80	0.81	0.31	0.00	3.92	8.09	6.43
KH-29	0.78	0.93	0.58	0.06	2.35	1.62	0.47	0.13	0.01	2.23	4.57	5.25
KH-30	1.00	2.59	1.00	0.06	4.65	2.46	1.26	0.36	0.17	4.25	8.9	8.99
KH-31	1.13	1.42	0.76	0.07	3.38	1.55	1.06	0.29	0.31	3.20	6.58	5.47
KH-32	1.02	1.34	0.76	0.09	3.21	1.68	0.88	0.31	0.27	3.14	6.36	2.20
KH-33	0.91	1.10	0.79	0.06	2.86	1.98	0.55	0.06	0.04	2.63	5.48	8.39
KH-34	0.80	1.01	0.59	0.05	2.45	1.81	0.45	0.12	0.06	2.43	4.88	0.82
KH-35	0.87	1.21	0.91	0.06	3.04	2.07	0.58	0.10	0.06	2.81	5.85	7.86
KH-36	1.27	1.02	0.98	0.05	3.32	2.34	0.53	0.27	0.01	3.15	6.47	5.26
KH-37	0.93	0.96	0.65	0.06	2.60	2.56	0.13	0.02	0.01	2.71	5.31	-4.14
KH-38	1.19	2.11	1.35	0.07	4.72	3.22	0.99	0.13	0.02	4.36	9.08	7.93
KH-39	1.08	1.74	1.18	0.06	4.06	2.50	1.02	0.15	0.05	3.73	7.79	8.47
KH-40	0.78	0.86	0.54	0.05	2.23	1.84	0.36	0.06	0.00	2.26	4.5	-1.33
KH-41	0.98	1.25	0.63	0.05	2.92	2.30	0.37	0.03	0.00	2.70	5.62	7.83
KH-42	1.05	1.26	0.76	0.05	3.12	2.56	0.34	0.04	0.00	2.94	6.06	5.94
KH-43	0.87	1.21	0.65	0.05	2.79	2.42	0.34	0.08	0.00	2.84	5.63	-1.78
KH-44	0.98	1.57	0.88	0.06	3.49	2.94	0.29	0.05	0.00	3.28	6.77	6.20
KH-45	0.87	1.14	0.68	0.06	2.75	2.38	0.29	0.06	0.00	2.73	5.48	0.73
KH-46	0.88	1.13	0.62	0.07	2.69	1.88	0.74	0.12	0.15	2.89	5.58	-7.17
KH-47	1.23	1.42	0.88	0.06	3.59	2.67	0.59	0.09	0.01	3.36	6.95	6.62
KH-48	1.30	0.89	0.59	0.05	2.83	1.93	0.18	0.01	0.01	2.13	4.96	28.23
KH-49	2.54	0.74	0.42	0.05	3.74	3.06	0.53	0.01	0.00	3.60	7.34	3.81
KH-50	0.87	0.90	0.44	0.05	2.27	2.01	0.23	0.01	0.00	2.25	4.51	0.89
KH-51	0.91	0.87	0.47	0.05	2.31	2.03	0.15	0.00	0.00	2.18	4.49	5.79
KH-52	0.96	0.86	0.42	0.05	2.29	2.03	0.08	0.01	0.00	2.12	4.41	7.71
KH-53	0.72	0.94	0.55	0.05	2.26	1.68	0.39	0.03	0.15	2.25	4.51	0.44
KH-54	1.35	1.11	0.64	0.10	3.20	2.61	0.28	0.04	0.06	3.00	6.2	6.45
KH-55	0.61	0.81	0.40	0.06	1.88	1.51	0.28	0.02	0.21	2.03	3.91	-7.67
KH-56	0.83	0.93	0.51	0.06	2.33	1.85	0.25	0.06	0.05	2.21	4.54	5.29

Appendix 5.12 Result of chemical analyses with ionic balance check

Sample	Cations meq/l					Anions meq/l						
Sample	Na^+	Ca^{2+}	Mg^{2+}	K^+	Tot^+	HCO_3^-	Cl^-	SO_4^{2-}	$NO3^-$	Tot^-	TDI	Balance %
KH-57	1.17	1.85	0.97	0.09	4.07	2.38	1.14	0.38	0.19	4.09	8.16	-0.49
KH-58	2.02	4.03	2.60	0.08	8.73	4.70	1.78	0.66	0.39	7.53	16.3	14.76
KH-59	1.02	1.66	1.20	0.06	3.95	2.68	1.03	0.34	0.19	4.24	8.19	-7.08
KH-60	1.04	1.62	1.10	0.06	3.82	2.61	0.65	0.15	0.05	3.47	7.28	9.62
KH-61	1.41	2.14	1.34	0.05	4.94	2.53	1.86	0.26	0.11	4.76	9.7	3.71
KH-62	0.91	1.34	0.78	0.05	3.08	2.30	0.55	0.10	0.00	2.96	6.05	3.97
KH-63	6.47	4.26	2.50	0.10	13.33	3.06	6.79	1.83	0.43	12.10	25.4	9.67
KH-64	1.37	2.24	1.37	0.06	5.04	2.89	1.26	0.36	0.18	4.69	9.73	7.19
KH-65	1.03	1.69	0.85	0.05	3.62	1.98	0.47	0.06	0.07	2.58	6.19	33.60
KH-66	0.61	0.79	0.35	0.07	1.81	1.24	0.28	0.01	0.09	1.62	3.44	11.05
KH-67	0.74	0.85	0.51	0.04	2.15	1.85	0.22	0.01	0.05	2.12	4.27	1.41
KH-68	0.62	0.73	0.40	0.06	1.81	1.17	0.59	0.00	0.08	1.84	3.65	-1.64
KH-69	0.70	0.95	0.61	0.04	2.31	1.91	0.23	0.00	0.00	2.15	4.45	7.19
KH-70	0.73	0.95	0.57	0.04	2.30	1.53	0.66	0.02	0.00	2.21	4.51	3.99
KH-71	0.89	1.09	0.58	0.04	2.60	1.85	0.20	0.01	0.07	2.12	4.72	20.34
KH-72	0.69	0.86	0.53	0.04	2.12	1.64	0.39	0.00	0.00	2.05	4.17	3.36
KH-73	0.68	0.98	0.58	0.05	2.29	1.73	0.39	0.00	0.00	2.12	4.4	7.73
KH-74	0.74	1.07	0.69	0.05	2.55	1.26	0.85	0.26	0.22	2.58	5.13	-1.17
KH-75	1.50	1.57	1.08	0.18	4.33	2.76	0.87	0.27	0.23	4.13	8.46	4.73
KH-76	0.98	3.32	1.89	0.19	6.38	4.88	0.94	0.00	0.13	5.95	12.3	6.97
KH-77	0.78	2.98	1.36	0.10	5.23	4.35	0.16	0.28	0.00	4.79	10	8.78
KH-78	3.84	2.05	0.99	0.31	7.18	4.22	1.91	0.39	0.19	6.71	13.9	6.77
KH-79	1.35	1.24	0.64	0.04	3.27	2.33	0.17	0.02	0.01	2.53	5.8	25.52
KH-80	1.01	0.96	0.56	0.04	2.57	2.22	0.14	0.00	0.00	2.37	4.94	8.10
KH-81	1.01	1.04	0.74	0.04	2.84	2.17	0.15	0.00	0.00	2.32	5.16	20.16
KH-82	0.83	0.62	0.36	0.04	1.85	1.73	0.08	0.00	0.00	1.81	3.66	2.19
KH-83	0.93	0.79	0.28	0.04	2.05	1.96	0.13	0.01	0.00	2.10	4.15	-2.41
KH-84	0.83	0.73	0.32	0.03	1.91	1.84	0.10	0.02	0.05	2.01	3.92	-5.10
KH-85	0.91	0.79	0.46	0.04	2.19	1.86	0.22	0.01	0.00	2.08	4.28	5.14
KH-86	0.93	0.94	0.47	0.04	2.38	1.88	0.44	0.02	0.01	2.34	4.72	1.69
KH-87	0.97	0.72	0.42	0.04	2.15	2.04	0.07	0.00	0.00	2.12	4.26	1.41
KH-88	1.83	2.74	1.20	0.14	5.92	3.70	1.18	0.37	0.21	5.45	11.4	8.27
KH-89	1.36	1.73	1.12	0.05	4.25	3.22	0.53	0.24	0.00	3.98	8.24	6.55
KH-90	1.29	2.34	1.36	0.06	5.04	2.47	1.40	0.67	0.34	4.88	9.93	3.22
KH-91	1.93	2.68	1.41	0.15	6.17	3.22	1.55	0.73	0.30	5.79	12	6.35
KH-92	1.19	2.33	1.32	0.12	4.96	3.09	1.05	0.42	0.04	4.60	9.56	7.53
KHS 1	0.54	0.48	0.37	0.01	1.44	1.08	0.22	0.03	0.00	1.33	2.77	8.03
KHS 2	1.33	2.12	1.30	0.03	4.83	1.60	2.17	0.30	0.32	4.38	9.22	9.74
KHS 3	1.29	2.61	1.54	0.04	5.53	1.64	3.07	0.03	0.38	5.12	10.65	7.60
KHS 4	1.07	1.93	1.49	0.04	4.54	2.52	1.11	0.61	0.00	4.24	8.78	6.83
KHS 5	1.15	2.78	2.62	0.07	6.68	3.04	1.58	1.38	0.06	6.05	12.73	9.78
KHS 6	0.92	1.01	0.77	0.02	2.75	2.32	0.30	0.01	0.00	2.63	5.37	4.37
KHS 7	3.61	7.88	5.17	0.13	16.82	9.88	5.64	0.26	0.00	15.78	32.60	6.38
KHS 8	1.58	2.52	1.69	0.04	5.84	3.84	0.97	0.56	0.01	5.39	11.23	8.12
KHS 9	2.13	3.00	1.65	0.04	6.84	4.88	1.28	0.54	0.00	6.70	13.54	1.97
KHS 10	2.39	2.24	1.78	0.05	8.05	4.20	2.10	0.68	0.59	7.56	15.61	6.29
KHS 11	1.88	2.52	1.81	0.05	6.48	4.20	1.18	0.42	0.08	5.88	12.37	9.65
KHS 12	1.99	3.78	1.96	0.05	8.69	5.84	1.61	0.30	0.12	7.87	16.56	9.87
KHS 13	0.63	1.07	0.66	0.02	2.43	1.78	0.52	0.00	0.00	2.31	4.74	5.27
KHS 14	1.04	1.61	0.77	0.02	3.48	3.08	0.18	0.05	0.00	3.31	6.78	4.99
KHS 15	0.77	5.89	1.87	0.05	8.63	7.00	0.48	0.43	0.00	7.90	16.53	8.77
KHS 16	1.30	3.77	2.62	0.07	7.82	5.60	1.42	0.30	0.00	7.32	15.14	6.49
KHS 17	0.97	2.17	1.27	0.03	4.47	3.20	0.90	0.01	0.00	4.10	8.57	8.63
KHS 18	2.01	3.92	2.53	0.06	8.55	3.60	3.29	1.63	0.00	8.52	17.06	0.35

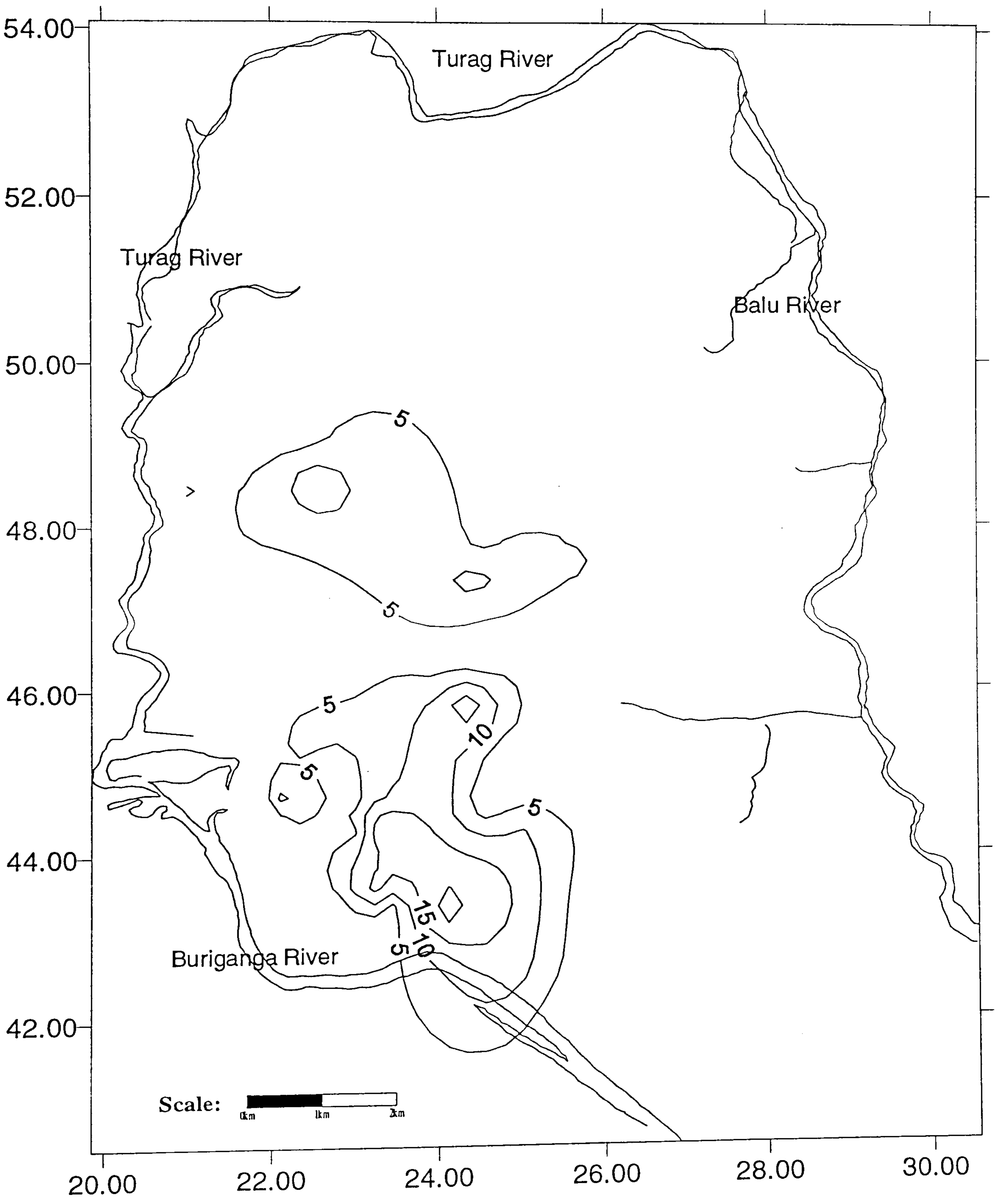
Appendix [illegible] Result of chemical analyses (trace components)

Sample	Al	B	Ba	Cd	Cr	Mn	Ni	Pb	Sr	Zn	F	PO_4
KH-1	0.05	0.02	0.05	0.00	0.00	0.19	0.00	0.05	0.34	0.01	-----	0.00
KH-2	0.05	0.03	0.07	0.01	0.00	0.17	0.00	0.05	0.34	0.04	-----	0.00
KH-3	0.06	0.02	0.05	0.00	0.01	0.15	0.01	0.06	0.40	0.01	0.00	0.00
KH-4	0.04	0.02	0.04	0.00	0.00	0.11	0.02	0.03	0.25	0.00	-----	0.00
KH-5	0.06	0.03	0.08	0.01	0.01	0.07	0.01	0.14	1.30	0.01	0.00	2.81
KH-6	0.04	0.02	0.03	0.00	0.00	0.20	0.00	0.02	0.23	0.00	0.00	2.98
KH-7	0.05	0.03	0.06	0.01	0.00	0.06	-----	0.04	0.32	0.01	0.00	0.00
KH-8	0.05	0.05	0.08	0.01	0.00	0.14	0.01	0.07	0.37	0.01	0.00	0.00
KH-9	0.05	0.03	0.07	0.01	0.00	0.06	0.03	0.07	0.48	0.02	-----	0.00
KH-10	0.06	0.04	0.08	0.01	0.01	0.08	0.00	0.08	0.44	0.08	0.00	0.00
KH-11	0.04	0.02	0.04	0.01	0.00	0.23	0.00	0.06	0.30	0.01	0.00	0.00
KH-12	0.04	0.02	0.05	0.01	0.00	0.09	0.01	0.05	0.28	0.01	0.00	0.00
KH-13	0.04	0.01	0.03	0.01	0.00	0.02	0.00	0.05	0.26	0.00	0.00	0.00
KH-14	0.03	0.01	0.01	0.00	0.00	0.02	-----	0.03	0.11	0.00	2.75	2.85
KH-15	0.04	0.02	0.04	0.01	0.01	0.24	0.02	0.08	0.36	0.01	0.00	0.00
KH-16	0.04	0.01	0.02	0.00	0.00	0.05	-----	0.02	0.11	0.00	0.00	0.00
KH-17	0.05	0.05	0.03	0.01	0.00	1.22	0.02	0.10	0.43	0.01	0.25	0.00
KH-18	0.03	0.02	0.02	0.00	0.00	0.09	0.01	0.03	0.11	0.00	0.20	0.00
KH-19	0.03	0.02	0.01	0.00	-----	0.02	-----	0.02	0.11	-----	0.00	0.00
KH-20	0.04	0.02	0.05	0.01	0.00	0.27	0.02	0.05	0.29	0.01	0.00	0.00
KH-21	0.04	0.02	0.04	0.00	0.00	0.06	0.00	0.05	0.30	0.01	0.00	0.00
KH-22	0.04	0.01	0.02	0.01	-----	0.00	0.02	0.03	0.15	0.00	0.01	0.00
KH-23	0.04	0.02	0.03	0.00	0.00	0.07	-----	-----	0.11	0.00	0.01	0.00
KH-24	0.05	0.01	0.02	0.01	0.00	0.09	0.01	0.05	0.18	0.07	0.00	0.28
KH-25	0.04	0.01	0.02	0.00	0.00	0.03	-----	0.04	0.14	0.00	0.40	0.00
KH-26	0.04	0.02	0.02	0.00	-----	0.05	0.00	0.02	0.11	1.58	0.33	0.37
KH-27	0.04	0.01	0.03	0.00	0.00	0.00	0.01	0.03	0.10	0.02	0.00	0.27
KH-28	0.04	0.01	0.03	0.01	0.00	0.00	0.00	0.03	0.25	0.01	0.00	0.00
KH-29	0.03	0.01	0.02	0.00	0.00	0.06	-----	0.02	0.12	0.01	0.17	0.53
KH-30	0.06	0.02	0.04	0.00	0.01	0.07	0.03	0.10	0.20	0.01	0.06	0.00
KH-31	0.04	0.04	0.03	0.00	0.01	0.06	-----	0.04	0.21	0.01	0.00	0.00
KH-32	0.04	0.03	0.03	0.00	0.01	0.07	-----	0.03	0.20	0.01	0.09	0.00
KH-33	0.05	0.01	0.05	0.01	0.00	0.11	-----	0.05	0.15	0.01	0.00	0.00
KH-34	0.04	0.01	0.03	0.01	0.00	0.05	0.00	0.03	0.13	------	0.11	0.00
KH-35	0.05	------	0.03	0.00	0.00	0.05	0.04	0.06	0.15	0.01	0.00	0.00
KH-36	0.04	0.02	0.03	0.01	0.00	0.51	0.00	0.04	0.17	0.00	0.56	0.29
KH-37	0.04	0.02	0.04	0.00	0.00	0.19	0.00	0.07	0.12	------	0.11	0.34
KH-38	0.04	0.01	0.03	0.01	0.01	0.02	------	0.07	0.26	0.01	0.09	0.25
KH-39	0.04	0.01	0.07	0.00	-----	0.02	0.01	0.04	0.20	0.16	0.00	0.00
KH-40	0.04	0.01	0.01	0.00	0.01	0.03	------	0.05	0.11	0.03	0.54	0.09
KH-41	0.04	0.01	0.03	0.01	0.00	0.01	0.02	0.06	0.16	0.00	0.00	0.00
KH-42	0.04	0.02	0.02	0.01	0.01	0.02	0.01	0.03	0.16	0.01	0.00	0.00
KH-43	0.04	0.01	0.03	0.00	0.00	0.01	0.01	0.04	0.15	0.00	0.00	0.00
KH-44	0.06	0.01	0.03	0.01	0.00	0.03	0.01	0.05	0.20	0.02	0.00	0.00
KH-45	0.04	0.01	0.05	0.01	0.00	0.04	------	0.05	0.15	0.45	0.00	0.00
KH-46	0.06	------	0.04	0.00	0.01	0.04	0.01	0.04	0.14	0.13	0.00	0.00
KH-47	0.05	0.02	0.02	0.01	0.01	0.02	0.03	0.06	0.17	0.01	0.59	0.00
KH-48	0.04	0.02	0.03	0.01	------	0.03	------	0.04	0.11	------	0.09	0.00
KH-49	0.04	0.02	0.02	0.00	-----	0.03	-----	0.03	0.09	------	0.22	0.00
KH-50	0.05	0.01	0.02	0.00	0.00	0.03	0.01	0.01	0.13	0.01	0.13	0.00
KH-51	0.05	0.01	0.03	0.01	0.00	0.05	0.01	0.06	0.12	0.10	0.32	0.00
KH-52	0.05	0.01	0.01	0.00	0.01	0.00	0.01	0.05	0.12	0.06	0.00	0.00
KH-53	0.03	0.01	0.02	0.00	0.00	0.00	0.02	0.04	0.13	0.01	0.25	0.00
KH-54	0.04	0.01	0.03	0.01	0.01	0.01	0.00	0.05	0.16	0.01	0.32	0.00
KH-55	0.05	0.01	0.02	0.01	0.01	0.02	0.00	0.04	0.13	0.01	0.00	0.00
KH-56	0.05	0.01	0.02	0.01	0.00	0.01	0.01	0.05	0.15	0.00	0.00	0.00
KH-57	0.07	0.01	0.05	0.01	0.01	0.03	0.00	0.05	0.28	0.01	0.00	0.00

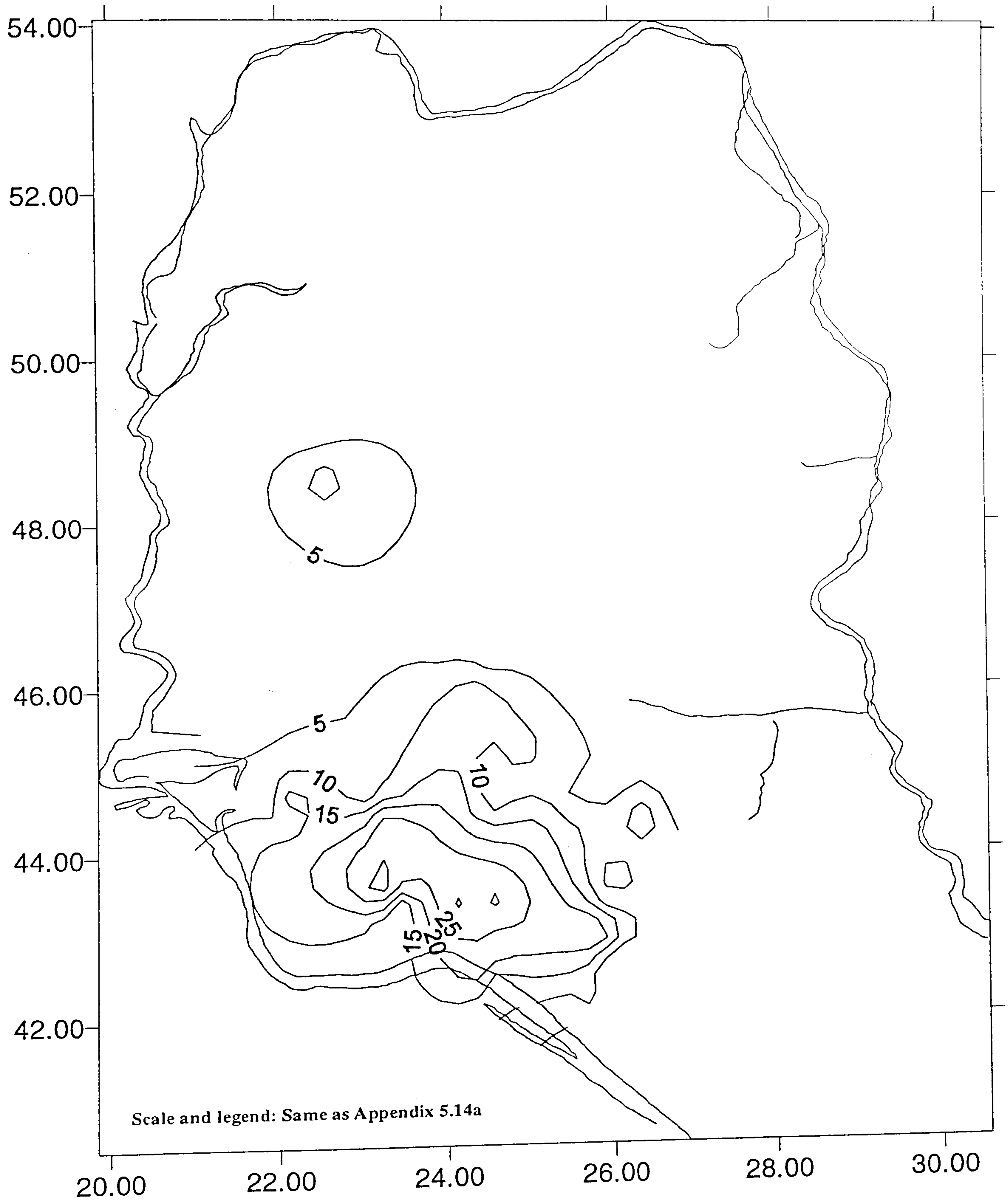
KH-57	0.07	0.01	0.05	0.01	0.01	0.03	0.00	0.05	0.28	0.01	0.00	0.00
KH-58	0.05	0.05	0.11	0.01	0.01	0.06	0.00	0.09	0.49	0.07	0.00	0.00
KH-59	0.04	0.01	0.04	0.01	0.00	0.10	------	0.06	0.20	0.00	0.05	0.29
KH-60	0.05	0.02	0.04	------	0.00	0.23	------	0.02	0.22	0.27	0.00	0.24
KH-61	0.07	0.02	0.03	0.01	0.00	0.11	------	0.04	0.28	0.10	0.00	0.00
KH-62	0.04	0.02	0.04	0.00	0.00	0.06	------	0.01	0.19	0.03	0.00	0.00
KH-63	0.04	0.13	0.10	0.01	0.01	0.12	0.06	0.10	0.59	0.01	0.00	0.00
KH-64	0.04	0.02	0.04	0.01	0.00	0.04	------	0.06	0.27	0.01	0.00	0.00
KH-65	0.04	0.01	0.04	0.01	0.00	0.04	0.02	0.06	0.21	0.00	0.00	0.00
KH-66	0.04	0.01	0.02	0.00	0.01	0.02	------	0.03	0.11	0.04	0.00	0.00
KH-67	0.04	0.01	0.02	0.00	0.00	0.03	0.02	0.04	0.11	**17.76**	0.10	0.00
KH-68	0.05	0.01	0.02	0.00	0.01	0.08	0.01	0.03	0.10	0.67	0.00	0.00
KH-69	0.05	0.01	0.01	0.00	0.00	0.05	0.01	0.03	0.12	0.04	0.00	0.00
KH-70	0.04	0.01	0.01	0.01	0.00	0.03	0.00	0.06	0.12	0.01	0.00	0.00
KH-71	0.05	------	0.03	0.00	0.01	0.03	0.04	0.06	0.14	0.02	0.00	0.00
KH-72	0.04	------	0.01	0.00	0.01	0.02	------	0.03	0.11	0.01	0.00	0.00
KH-73	0.05	0.01	0.03	0.00	0.00	0.07	------	0.03	0.13	0.01	0.00	0.00
KH-74	0.04	0.01	0.02	0.00	------	0.04	0.01	0.02	0.13	0.15	0.00	0.00
KH-75	0.04	0.03	0.04	0.00	0.00	0.00	0.03	0.05	0.16	0.02	0.21	0.29
KH-76	0.04	0.03	0.04	0.01	0.00	1.77	------	0.09	0.27	0.02	0.00	0.00
KH-77	0.03	0.03	0.18	0.01	0.00	0.20	0.00	0.09	0.29	0.01	0.00	0.00
KH-78	0.06	0.05	0.15	0.00	------	0.12	0.02	0.05	0.16	0.03	0.00	0.00
KH-79	0.03	0.01	0.03	0.00	0.00	0.13	------	0.03	0.16	0.05	0.79	0.00
KH-80	0.04	0.01	0.04	0.01	0.00	0.04	0.00	0.03	0.13	3.57	0.13	0.00
KH-81	0.03	0.02	0.04	0.00	------	0.06	0.01	0.03	0.13	0.15	0.00	0.00
KH-82	0.03	0.01	0.01	0.00	------	0.00	------	0.03	0.08	0.09	0.00	0.00
KH-83	0.03	0.01	0.02	0.00	------	0.01	------	0.03	0.10	0.01	0.93	0.00
KH-84	0.03	0.01	0.02	0.00	0.00	0.03	0.01	0.00	0.10	0.06	0.00	0.00
KH-85	0.03	0.01	0.01	0.00	0.00	0.02	0.00	0.01	0.11	0.10	0.08	0.33
KH-86	0.04	0.01	0.01	0.00	0.00	0.00	0.02	0.02	0.14	0.01	0.78	0.00
KH-87	0.04	0.01	0.02	0.00	0.00	0.01	0.00	0.03	0.09	1.68	0.00	0.00
KH-88	0.05	0.03	0.09	0.00	0.00	0.04	------	0.06	0.46	0.07	0.00	0.00
KH-89	0.04	0.02	0.03	0.01	0.00	0.04	------	0.07	0.22	0.03	0.00	0.00
KH-90	0.04	0.02	0.05	0.01	0.00	0.04	------	0.05	0.36	0.02	0.00	0.00
KH-91	0.04	0.08	0.06	0.01	------	0.04	------	0.06	0.49	0.01	0.00	0.00
KH-92	0.04	0.02	0.06	0.01	0.00	0.08	0.00	0.05	0.34	0.01	0.29	0.00
KHS 1	0.07	0	0.02	0	0.01	0.02	0.01	0.06	0.1	0.02	0.00	0.00
KHS 2	0.08	0	0.05	0.01	0.01	0.03	0.05	0.16	0.41	0.03	0.00	0.00
KHS 3	0.07	0.01	0.05	0.01	0.01	0.01	0.02	0.19	0.48	0.04	0.93	0.00
KHS 4	0.19	0.01	0.12	0.01	0.01	0.33	0.03	0.13	0.27	0.02	0.00	0.00
KHS 5	0.08	0.01	0.04	0.01	0.01	0.29	0.03	0.18	0.32	0.02	0.08	0.33
KHS 6	0.08	0.01	0.03	0.01	0.01	0.07	0.01	0.08	0.13	0.03	0.78	0.00
KHS 7	0.09	0.06	0.11	0.02	0.02	9.22	0.08	0.37	1.5	0.19	0.00	0.00
KHS 8	0.08	0.01	0.09	0.01	0.01	0.71	0.02	0.18	0.29	0.02	0.00	0.00
KHS 9	0.08	0.03	0.03	0.01	0.01	0.61	0.05	0.19	0.31	0.12	0.00	0.00
KHS 10	0.08	0.05	0.16	0.01	0.01	0.41	0.03	0.14	0.27	0.03	0.00	0.00
KHS 11	0.07	0.04	0.22	0.01	0.01	0.59	0.05	0.18	0.58	0.03	0.00	0.00
KHS 12	0.19	0.05	0.32	0.02	0.01	0.39	0.05	0.18	0.3	0.03	0.29	0.00
KHS 13	0.08	0.01	0.02	0.01	0.01	0.15	0.03	0.11	0.16	0.04	0.00	0.00
KHS 14	0.17	0	0.04	0.01	0.01	0.08	0.02	0.1	0.2	0.66	0.21	0.29
KHS 15	0.08	0.03	0.2	0.02	0.01	1.75	0.04	0.27	0.36	0.06	0.00	0.00
KHS 16	0.07	0.03	0.05	0.02	0.01	0.39	0.05	0.22	0.57	0.04	0.00	0.00
KHS 17	0.08	0.01	0.02	0.01	0.01	0.26	0.03	0.17	0.37	0.03	0.00	0.00
KHS 18	0.08	0.02	0.06	0.01	0.01	0.32	0.07	0.24	0.8	0.3	0.79	0.00
KHS 19	0.07	0	0.02	0.01	0.01	0.11	0.03	0.08	0.13	0.02	0.2	0
KHS 20	0.08	0.01	0.02	0.01	0.01	0.29	0.03	0.16	0.25	0.08	0.3	0

------ Concentration below detection level

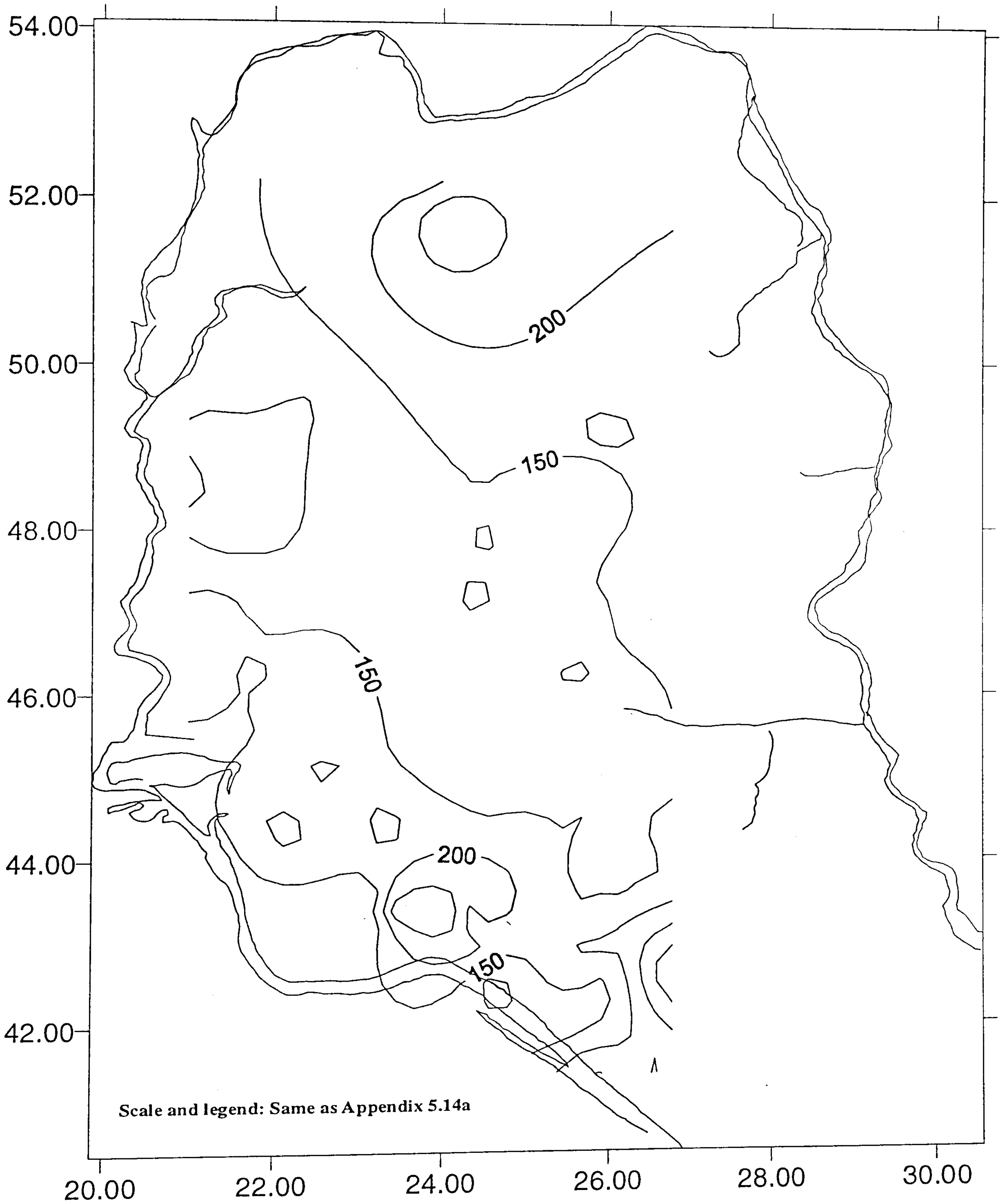
Appendix 5.14a Spatial distribution of nitrate (mg/l) in the Dhaka aquifer



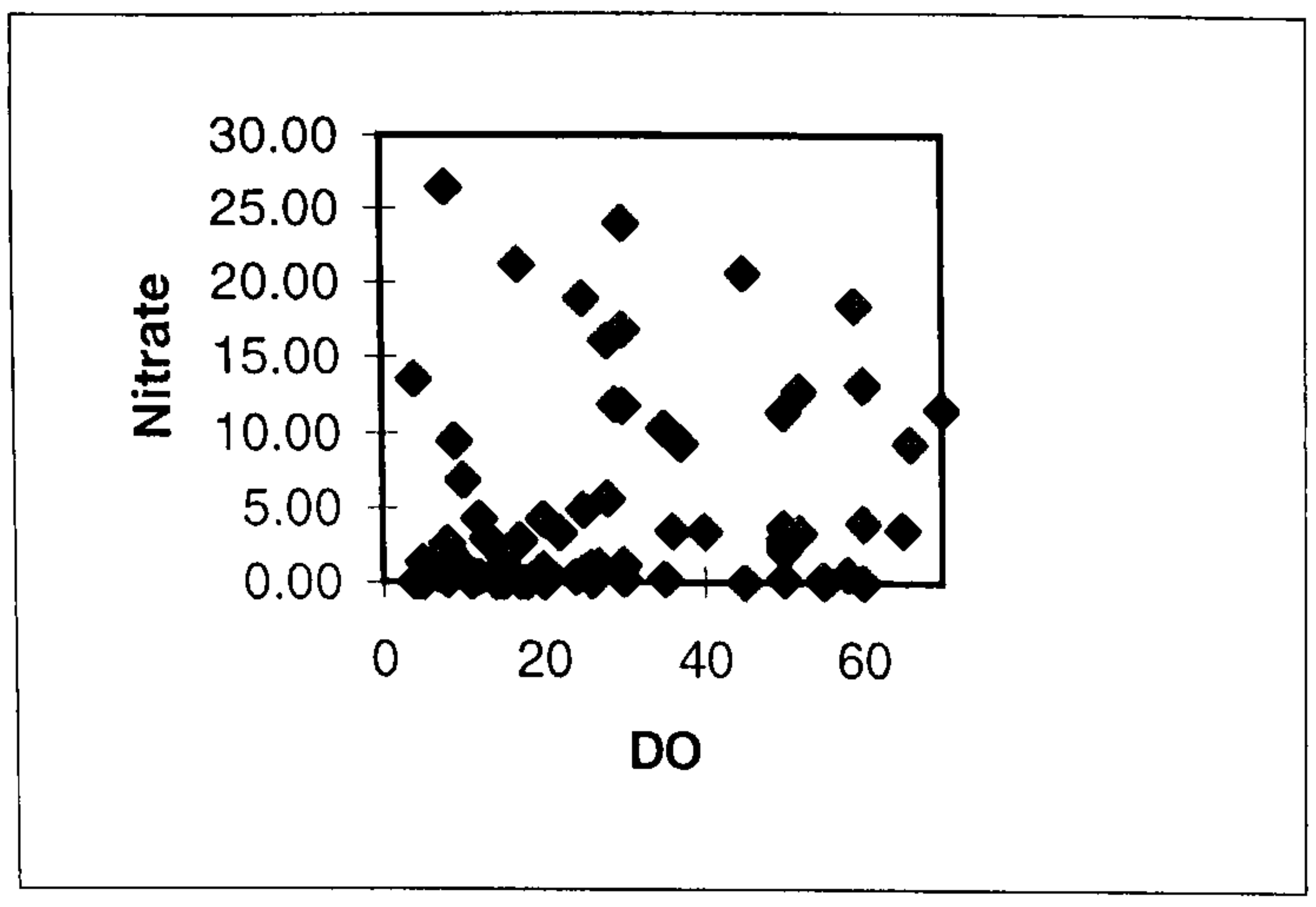
Appendix 5.14b Spatial distribution of sulphate (mg/l) in the Dhaka aquifer

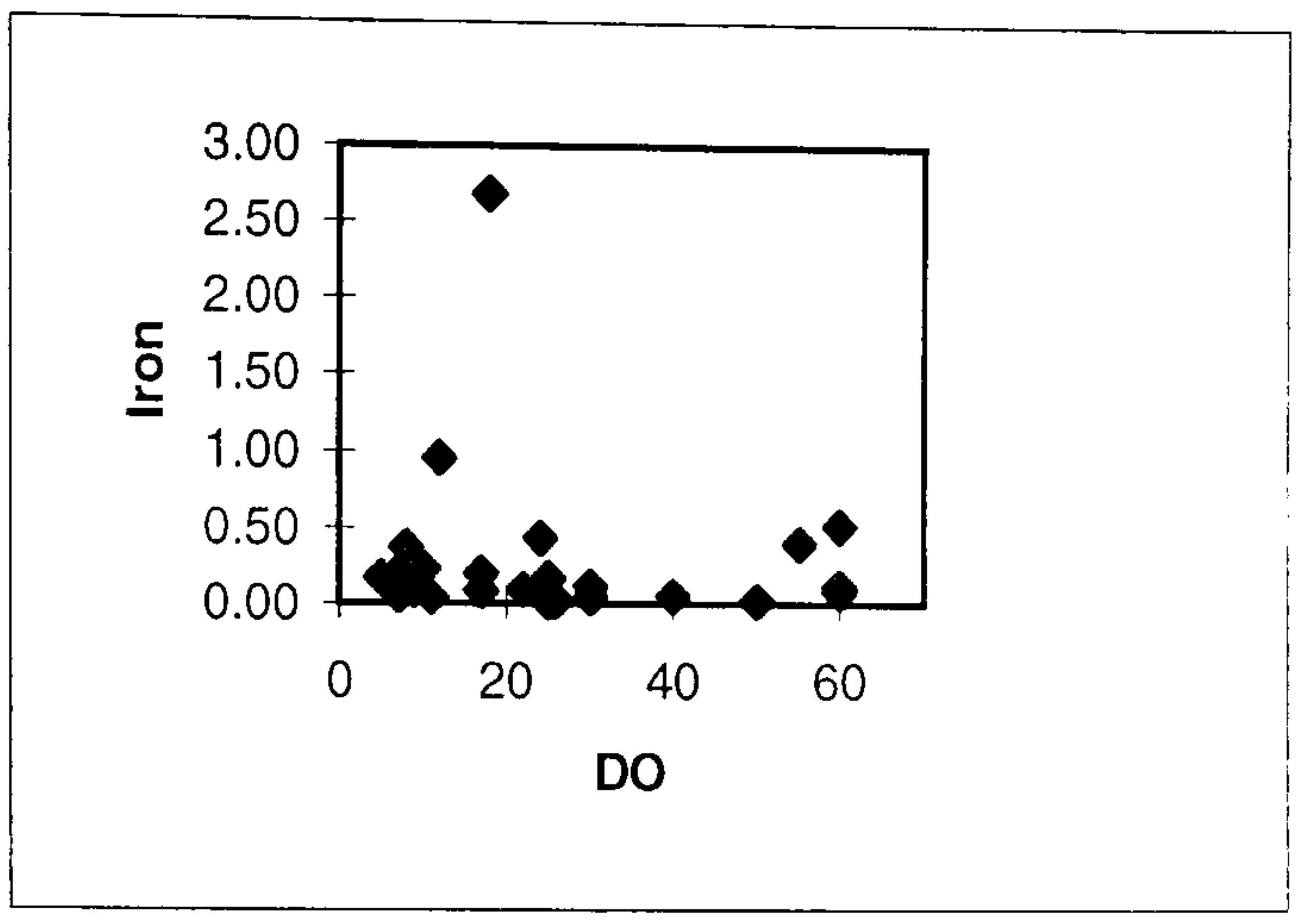


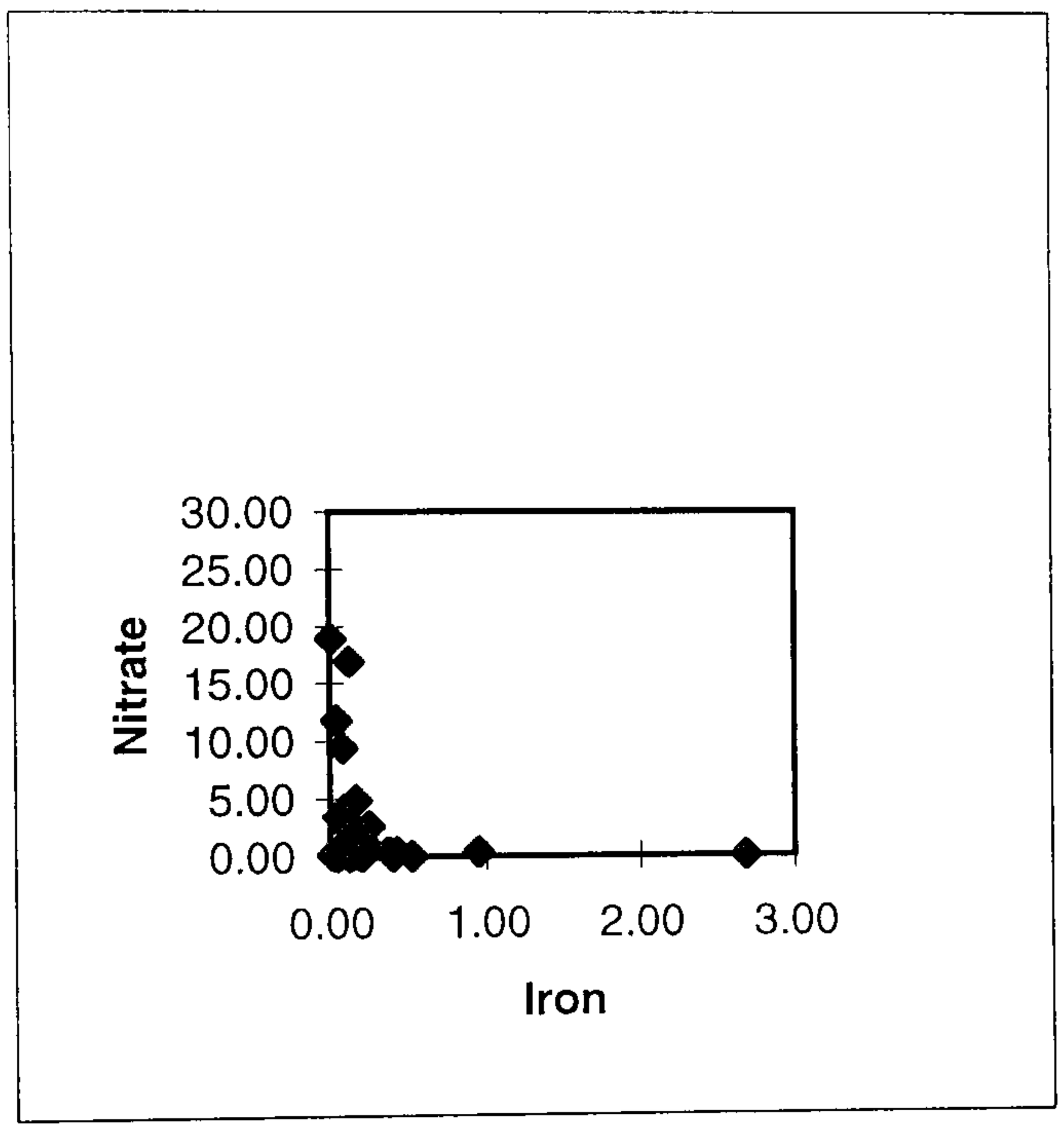
Appendix 5.14c Spatial distribution of bicarbonate (mg/l) in the Dhaka aquifer

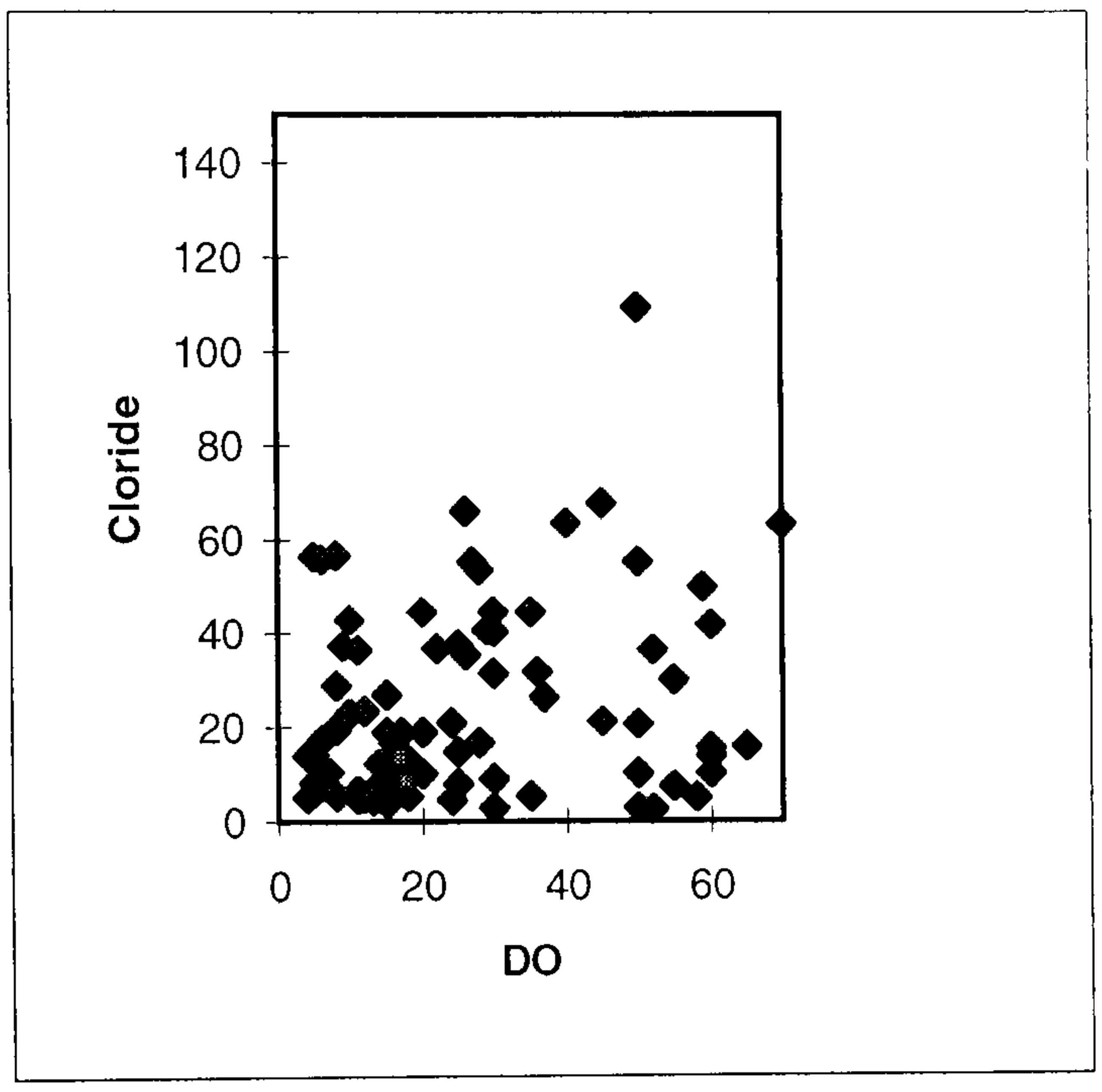


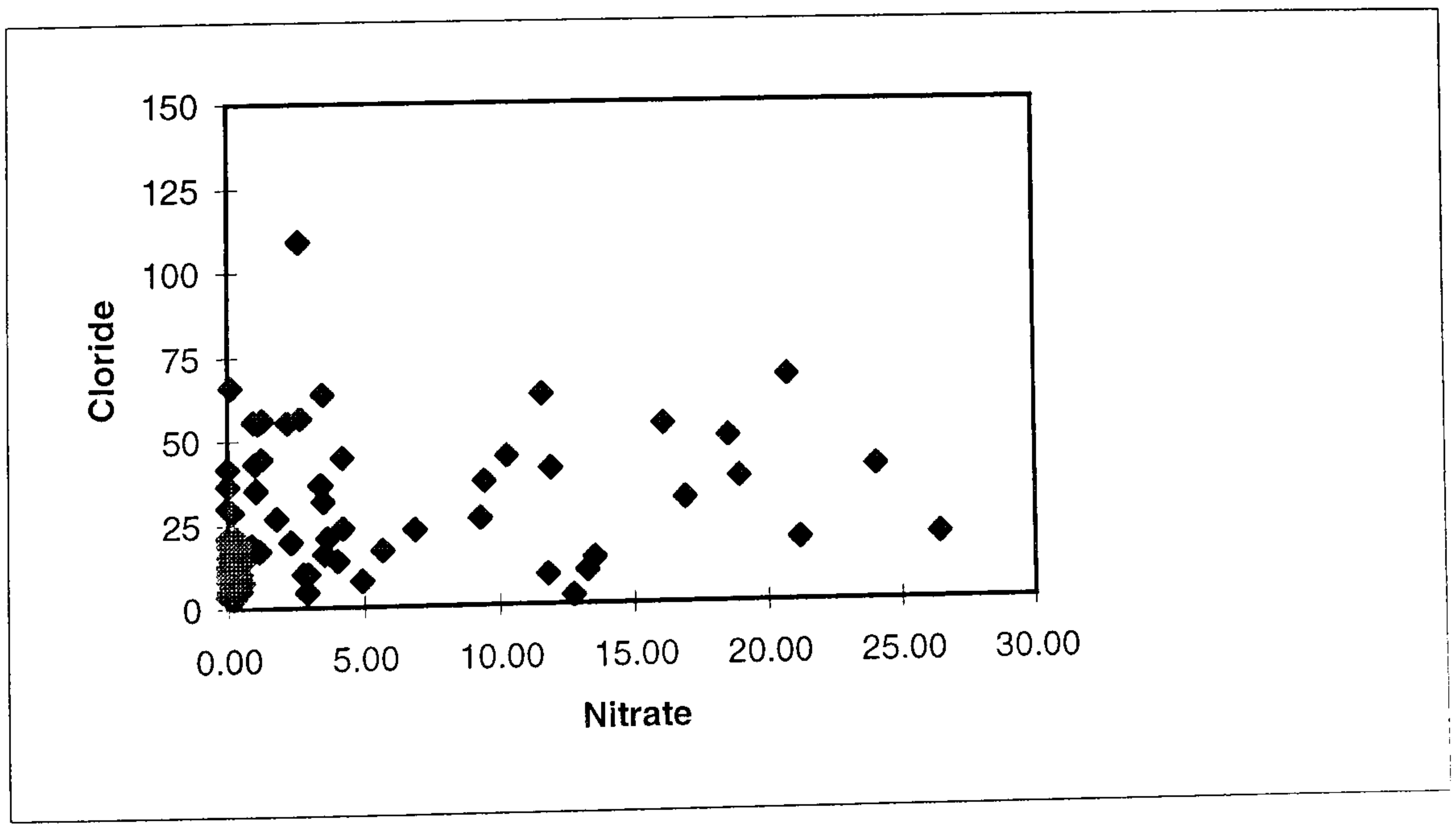
Appendix 5.15 Relationships between the redox sensitive parameters (DTWs) DO, nitrate and iron and between DO and choride (all units are in mg/l except DO which is % of saturation)



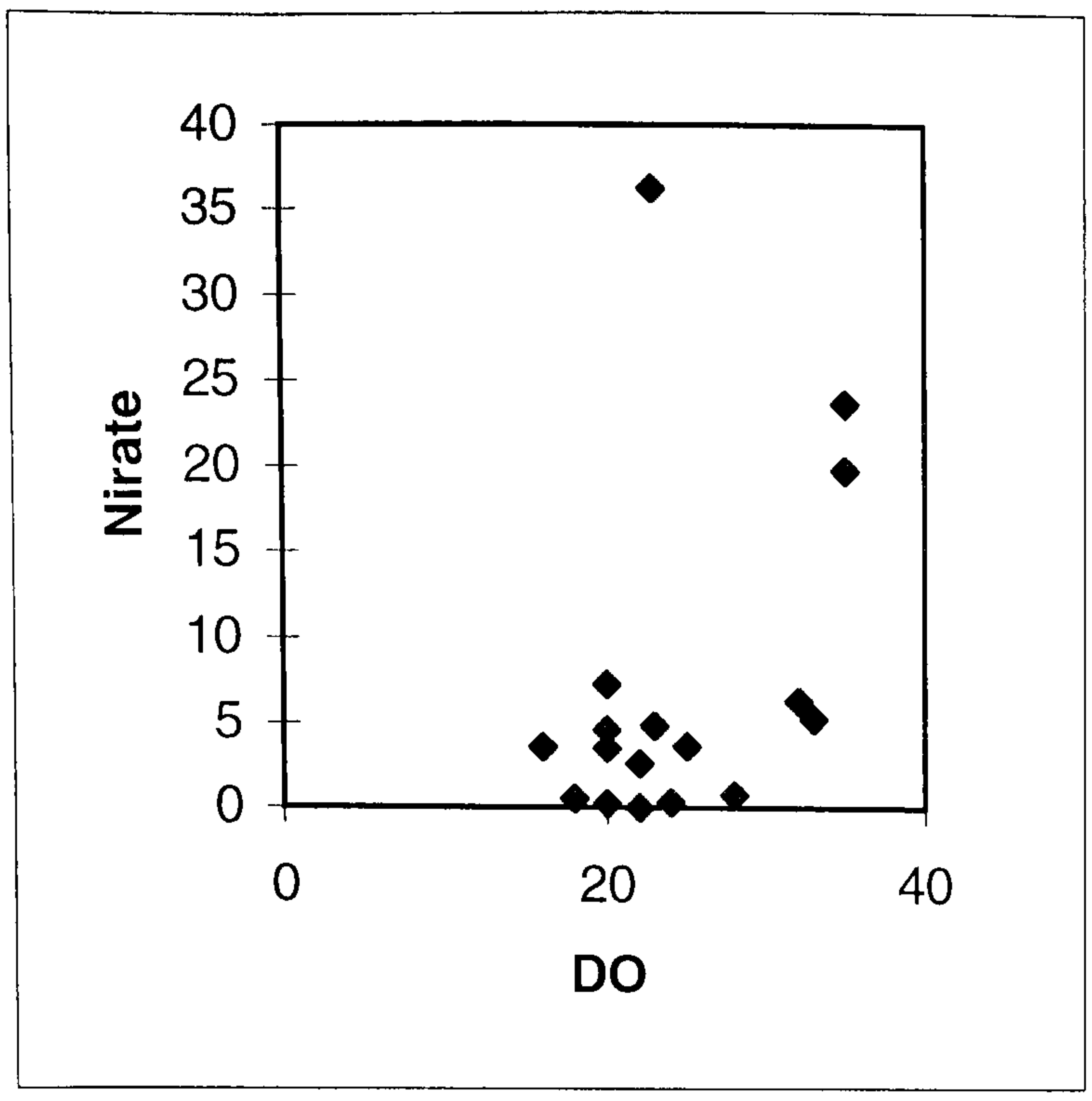


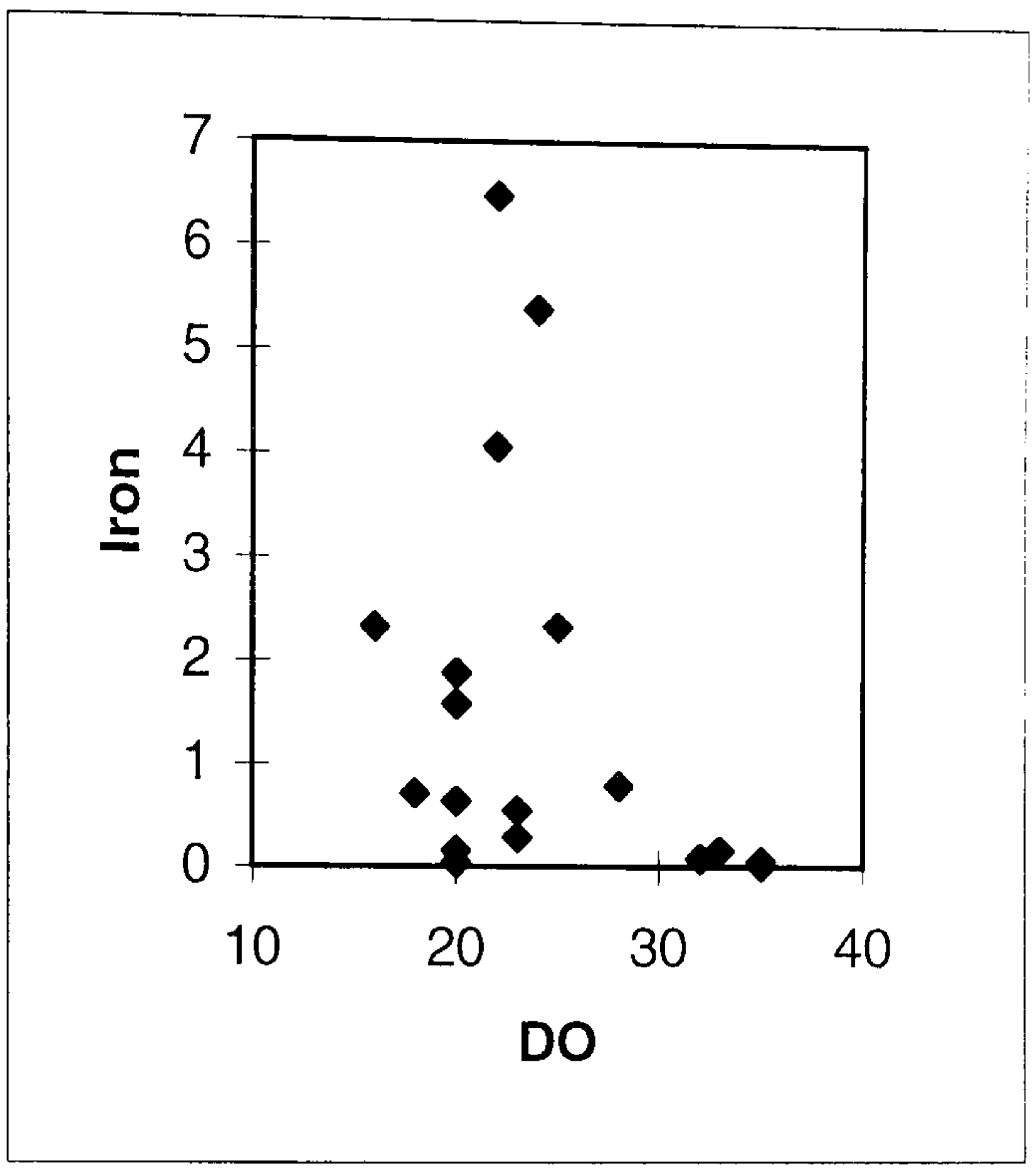


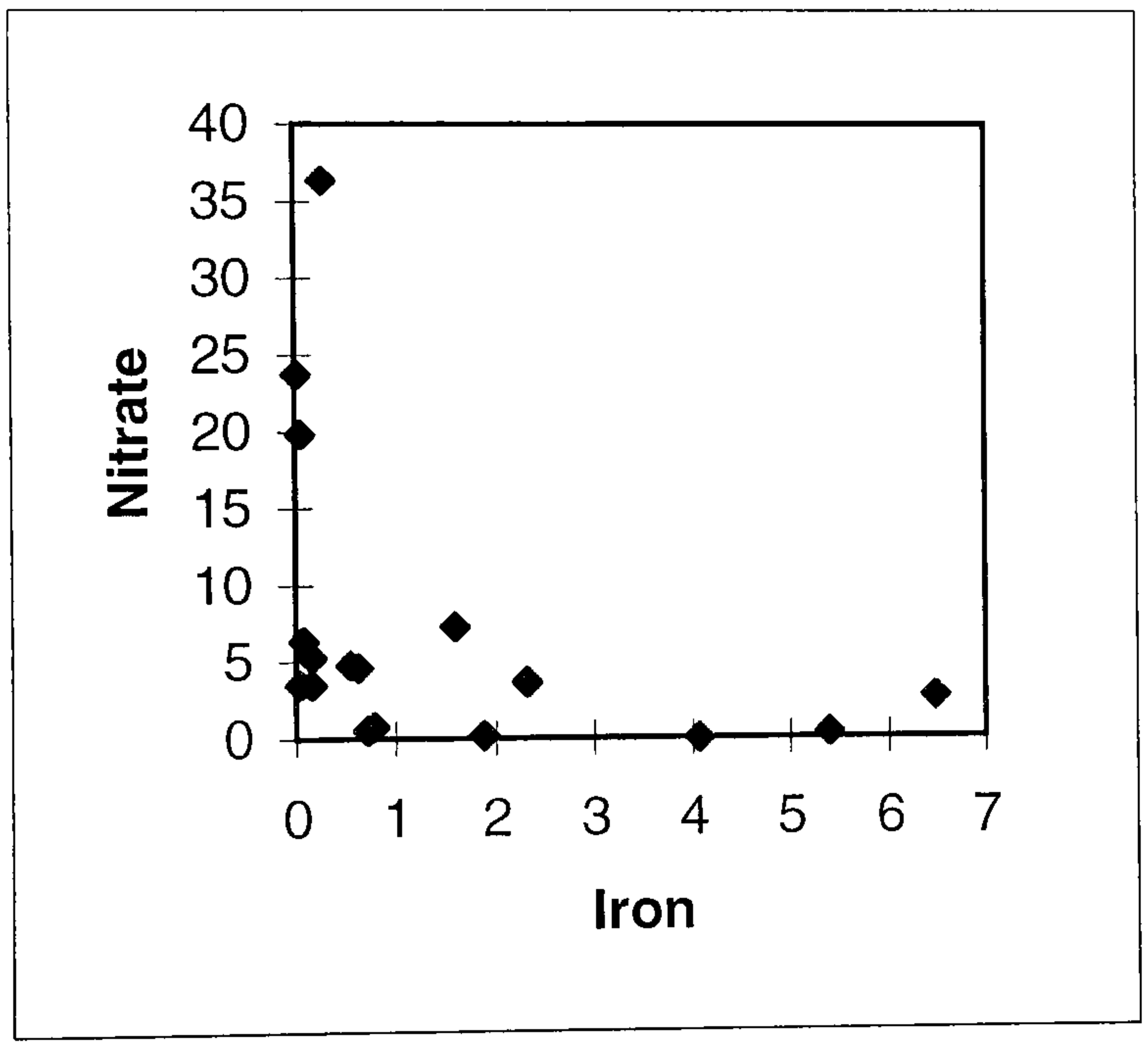


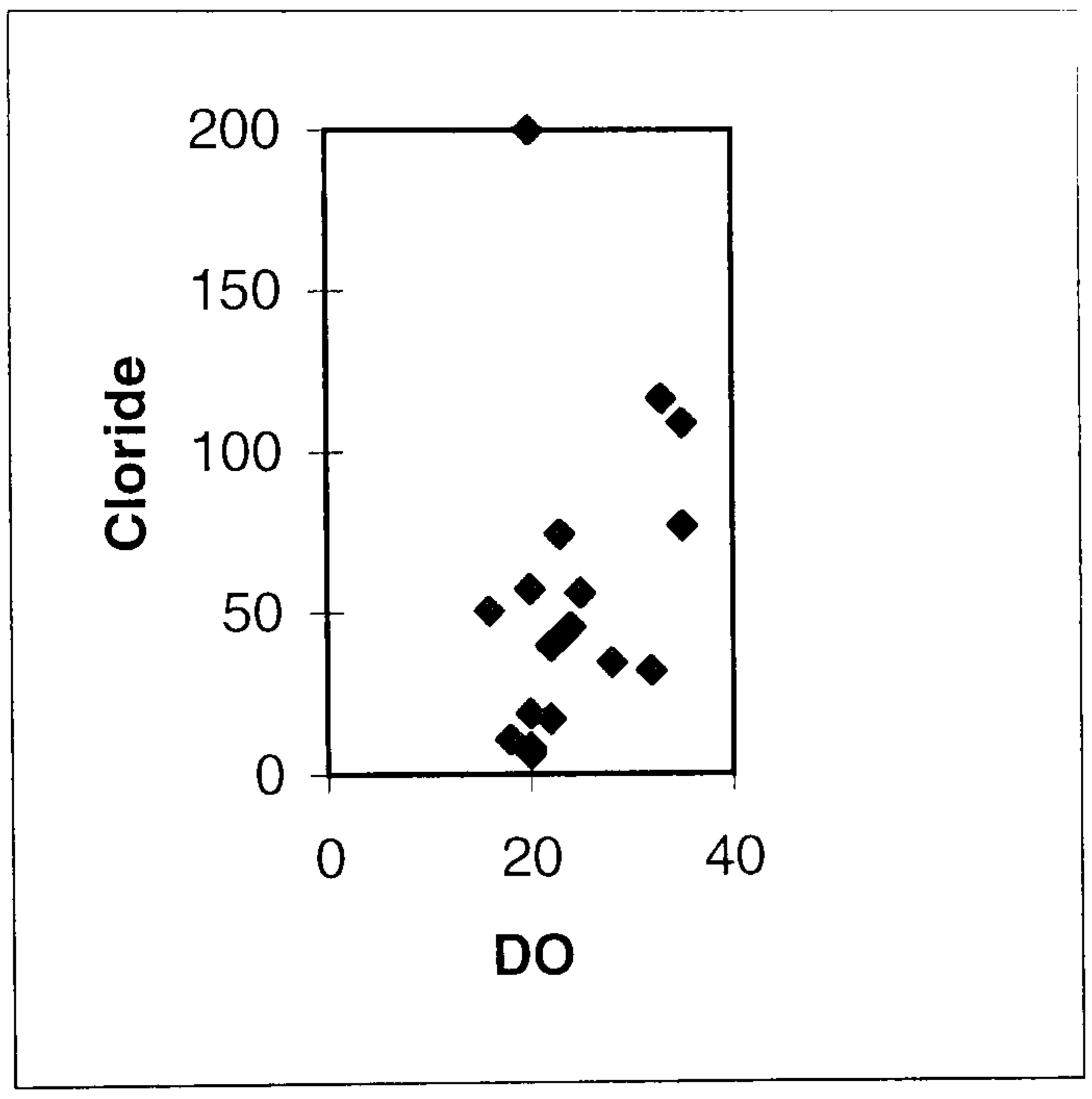


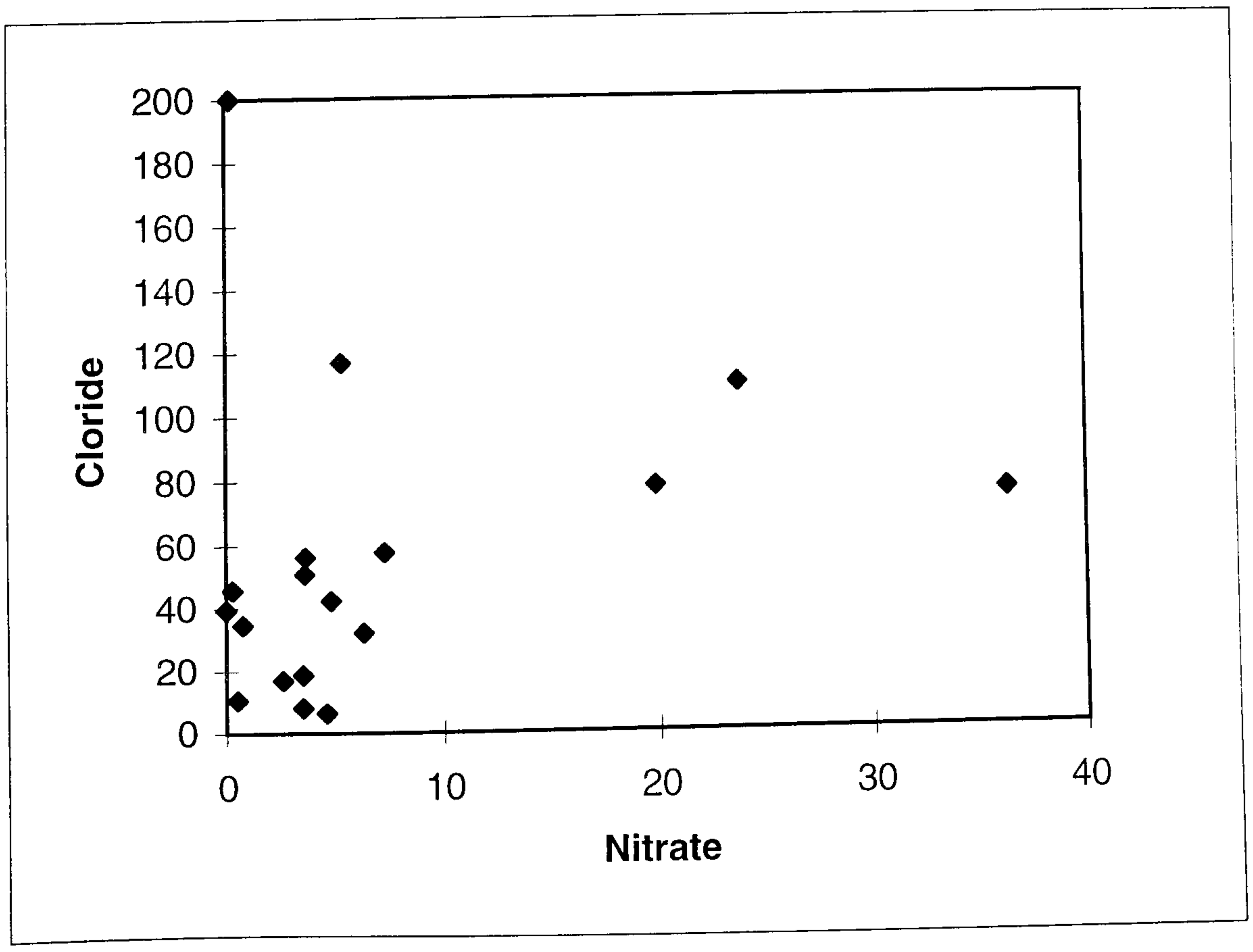
Appendix 5.15 Relationships between the redox sensitive parameters (STWs) DO, nitrate and iron and between DO and chloride (all units are in mg/l except DO which is % of saturation)











Appendix 5.16 Result of chemical analyses of 'field blank' sampels

Result of chemical analyses in mg/l									
Sample	Cations mg/l				Anions mg/l				
	Na^+	Ca^{2+}	Mg^{2+}	K^+	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	TDS mg/l
BL-1	0.00	0.3	0.04	0.5	0.00	0.2	0.27	0.00	1.31
BL-2	0.00	0.2	0.04	0.2	0.00	0.72	0.24	0.00	1.40
BL-3	0.00	0.3	0.04	0.4	0.00	0.26	0.34	0.00	1.34
BL-4	0.00	0.2	0.06	0.4	0.00	0.2	0.28	0.00	1.14
BL-5	0.00	0.3	0.04	0.5	0.00	0.7	0.24	0.00	1.78
BL-6	0.00	0.3	0.05	0.3	0.00	0.4	0.48	0.00	1.53
BL-7	0.00	0.2	0.04	0.5	0.00	0.56	0.35	0.00	1.65
BL-8	0.00	0.2	0.05	0.5	0.00	0.55	0.37	0.00	1.67
BL-9	0.00	0.2	0.12	0.3	0.00	0.7	0.31	0.00	1.63
BL-10	0.00	0.2	0.06	0.4	0.00	0.72	0.21	0.00	1.59
BL-11	0.00	0.1	0.08	0.6	0.00	0.72	0.26	0.00	1.76
BL-12	0.00	0.2	0.08	0.4	0.00	0.72	0.2	0.00	1.60
BL-13	0.00	0.1	0.06	0.4	0.00	0.2	0.28	0.00	1.04
BL-14	0.00	0.2	0.04	0.3	0.00	0.65	0.15	0.00	1.34
BL-15	0.00	0.2	0.05	0.3	0.00	0.5	0.36	0.00	1.41
BL-16	0.00	0.2	0.04	0.5	0.00	0.56	0.41	0.00	1.71
BL-17	0.00	0.2	0.05	0.5	0.00	0.63	0.4	0.00	1.78

Results of Chemical analysis in meq/l with ionic balances												
Sample	Cations meq/l					Anions meq/l						
	Na^+	Ca^{2+}	Mg^{2+}	K^+	Tot^+	HCO3	Cl^-	SO_4^{2-}	NO3⁻	Tot^-	TDI	Balance %
BL-1	0.00	0.01	0.00	0.01	0.02	0.00	0.01	0.01	0.00	0.02	0.04	0.00
BL-2	0.00	0.01	0.00	0.01	0.02	0.00	0.02	0.00	0.00	0.02	0.04	-8.40
BL-3	0.00	0.01	0.00	0.01	0.02	0.00	0.01	0.01	0.00	0.03	0.06	0.00
BL-4	0.00	0.01	0.00	0.01	0.02	0.00	0.01	0.01	0.00	0.02	0.04	1.05
BL-5	0.00	0.01	0.00	0.01	0.03	0.00	0.02	0.00	0.00	0.02	0.05	11.49
BL-6	0.00	0.01	0.00	0.01	0.02	0.00	0.01	0.01	0.00	0.02	0.04	6.22
BL-7	0.00	0.01	0.00	0.01	0.02	0.00	0.02	0.01	0.00	0.02	0.05	-1.38
BL-8	0.00	0.01	0.00	0.01	0.02	0.00	0.02	0.01	0.00	0.03	0.05	1.96
BL-9	0.00	0.01	0.01	0.01	0.03	0.00	0.02	0.01	0.00	0.02	0.05	4.94
BL-10	0.00	0.01	0.00	0.01	0.03	0.00	0.02	0.00	0.00	0.03	0.05	1.87
BL-11	0.00	0.00	0.01	0.02	0.03	0.00	0.02	0.01	0.00	0.02	0.05	4.54
BL-12	0.00	0.01	0.01	0.01	0.03	0.00	0.02	0.00	0.00	0.02	0.05	9.05
BL-13	0.00	0.00	0.00	0.01	0.02	0.00	0.01	0.01	0.00	0.02	0.04	0.79
BL-14	0.00	0.01	0.00	0.01	0.02	0.00	0.02	0.00	0.00	0.02	0.04	-2.43
BL-15	0.00	0.01	0.00	0.01	0.02	0.00	0.01	0.01	0.00	0.02	0.04	0.77
BL-16	0.00	0.01	0.00	0.01	0.03	0.00	0.02	0.01	0.00	0.03	0.05	6.85
BL-17	0.00	0.01	0.00	0.01	0.03	0.00	0.02	0.01	0.00	0.03	0.05	2.96

Concentration of VOCs in 'field blank' samples					
Sample	Concentration in mg/l				
	Chloroform	Benzene	TCE	PCE	xylene
OBL-1	0.00	0.00	0.00	0.00	0.00
OBL-2	0.00	0.00	0.00	0.00	0.00
OBL-3	0.00	0.00	0.00	0.00	0.00
OBL-4	0.00	0.00	0.00	0.00	0.00
OBL-5	0.00	0.00	0.00	0.00	0.00

Appendix 6.1 BTEX/Chlorinated solvent analysis procedure used at Wolfson lab

Method based on U.S. Geological Survey Open File Report 94-708.
Methods of Analysis by the U.S. Geological Survey National Water Quality Laboratory: Determination of Volatile Organic Compounds in Water by Purge & Trap Capillary Gas Chromatography/Mass Spectrometry.

The following volatile organic compounds were looked for:
Benzene, Toluene, Ethylbenzene, m&p-Xylene, o-Xylene and TCA,PCE, TCE, CTC, Chloroform.

Analysis was carried out in the Wolfson Laboratory by Sarah L. Houghton using P&T GC/MS .

GC-MS analysis of VOC's was performed on a Tekmar 3000 Purge & Trap using a Precept II autosampler linked to a Fisons 8000 Series gas chromatograph interfaced to a MD 800 quadrople mass spectrometer (ionisation voltage, 70eV; and source temperature at 200°C, interface temperature 250°C). Separation was performed using a fused silica capillary column (25m × 0.32 mm i.d, SGE) coated (0.5μm) with 5% phenyl polysiloxane (BP5). The gas chromatograph was fitted with a split/splitless injector heated at 230°C. Helium was used as carrier gas with a head pressure of 50 pK_a . Initial oven temperature for the analytes was 30°C for 5 minutes, which was then ramped at 10°C/min to 100°C, followed by 20°C/min to 200°C, where it was held isothermally at 200°C for 5 minutes.

5ml of each sample was purged for 11 minutes and then desorbed for 10 minutes at 270°C from a VOCARB 3000 Purge Trap (K). The sample was then swept onto the GC column via the transfer line held at 130°C
The trap was preconditioned before use at 270°C for 60 minutes and was baked each morning for 15 mins at 280°C.

For the 13 samples run; 2 sets of calibration standards were analysed, and blanks before and after each sample as well as two samples of a mass spectrometer performance standard solution: 1-bromo-2-fluorobenzene (Supelco).
Calibration standards were made up in methanol (Distol grade, Fischer) and spiked in Ultrapure water (43ml) in EPA recommended autosampler vials (Alltech) to cover a concentration range from 1 to 20 ug/l (6 standards per set). The EPA 624 calibration mix 1 (Supelco) and o-, m- and p- xylenes (Supelco) were used.
An internal standard toluene-d_8 (Supelco) was used to check recovery, it was not used to correct the final results.